STEREOTOMY.

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PREFACE.

It is believed that, for some time, there has been a need for a text-book on stereotomy which should furnish, in addition to the valuable exercises in projections now given by a number of works, practical examples of modern masonry structures, directions for the preparation of drawings which are daily made by engineers and architects, and more of the practical detail of building stone masonry.

Chapters I and II are intended to give the student an outline of those features of masonry construction which must be in mind in properly drawing plans for stonework. In courses of study where masonry and foundations precedes stereotomy, much of the matter in these chapters might well be omitted. Article 4 of Chapter II is thought to contain all that is necessary for the direction of the work of preparing plaster models. The making of a perfect model by the student insures a complete understanding of the problem.

Chapters III and IV contain the problems of most frequent occurrence, and for many courses will furnish ample work for the class.

Chapter V, on the Oblique Arch, has been given at the suggestion of several professors, and it is thought that although the use of concrete and brick has removed the necessity of building skew-arches with spiral courses of cut stone, the problem is a valuable one for the student to master. Examples of the false skew-arch and the skew-arch with ribs are taken from late practice.

Chapter VI contains three problems of rare occurrence, and are given in condensed form.

No claim is made for originality in the text, the aim of the authors having been to select matter from older works, to condense where possible, add explanations where it was deemed necessary,

and to bring together matter that has been found scattered through many works.

It is hoped that the effort may be of value to teachers and students of our technical schools.

In the preparation of the articles on the Oblique Arch full acknowledgment must be made to the help received from Buck's "Essay on Oblique Bridges," to Crowell "On the Design and Construction of the Oakley Arch," to Dobson's "Masonry and Stone-cutting," and to several of the books and articles mentioned in the Bibliography of the Oblique Arch. As far as possible acknowledgment has been made in the text.

The authors wish also to acknowledge their indebtedness to Mr. E. F. Miner and the Norcross Bros., for kind permission to use Plates IV–VII, on the Worcester City Hall and on Church Masonry ; to Mr. H. P. Boardman, for information in regard to the construction of the Glasgow Bridge Piers (Plates XII and XIII) ; to Mr. W. J. Wilgus, M. Am. Soc. C. E., Chief Engineer of the New York Central and Hudson River Railroad, for permission to use Plate XV ; to the *Engineering News*, for use of half-tones (Figs. 40 and 41) ; to Mr. H. B. Seaman, M. Am. Soc. C. E., for Fig. 42 of the Pelham Arch; to Mr. A. S. Cheever, Ass't Chief Engineer of the Boston and Maine Railroad for permission to use Plate XIX; to Mr. Foster Crowell, M. Am. Soc. C. E., for suggestions on the method of treatment of the oblique arch, and for examples of this form of construction ; to Mr. Henry L. Fifield, of the senior class of the Institute, for his skill and patience in preparing the drawings for most of the plates and illustrations in the book ; to Prof. W. D. Pence, of Purdue University, to Prof. A. L. Smith of the Worcester Polytechnic Institute, and to numerous other professors in different institutions, for suggestions freely given; and especially to President E. A. Engler, of the Worcester Polytechnic Institute, for suggestions and criticism.

A. W. F.
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STEREOTOMY.

CHAPTER I.

DEFINITIONS AND CLASSIFICATIONS.

Art. 1. Description of Building Stones.

1. **TRAP** is an igneous rock of great strength and durability, but owing to its lack of cleavage and its exceeding toughness it is of little use as a building stone. Its principal use is as a road metal and as the aggregate for concrete.

2. **GRANITE** is a metamorphic, unstratified rock, the strongest and most durable of all the stones in common use. It generally breaks with regularity and can be quarried into simple shapes without difficulty. It is hard and tough and is not easily worked into elaborate forms. Its great use is for massive structures, such as piers, abutments, docks, and building walls, where simple blocks are required.

3. **LIMESTONES**, composed chiefly of carbonate of lime, are of great variety in color, composition, and usefulness for building purposes. Limestone is a sedimentary rock, stratified in layers of varying thickness.

The light-colored and fine-grained limestones are often sawed into ashlar, and thus worked make an excellent building material. They are generally less easily worked under the chisel than the sandstones. Some of the softer limestones, however, possess the valuable quality of being easily wrought when taken from the quarry, and of hardening after exposure and seasoning.

The cream-colored limestones of the Paris basin, Topeka stone of Kansas, and the Bermuda stone have all been used in building

walls that were planed down and elaborately ornamented at small expense.

4. **MARBLES.**—Commonly any limestone that will take a polish is termed a marble, but the name is properly applied to limestone that has been metamorphosed to a crystalline texture. Marbles are easily worked and form the most beautiful of building stones.

5. **SANDSTONES** are stratified rocks composed chiefly of grains of sand more or less cemented and consolidated. The size of the sand grains, the cementing material, the compactness of the grains, and the presence of other ingredients, such as lime, iron, alumina, magnesia, etc., modify the character, color, and durability of the sandstones.

When of nearly pure silica and well cemented, sandstones are as resistant to weather as granite, and very much less affected by the action of fire.

When first taken from the quarry they are frequently very soft, but on exposure become hard.

Sandstones are abundant in nearly all countries, are quarried with great ease, are wrought with the chisel much easier than granite, limestone, and most other building stones, and, taken as a whole, may be considered as among the most durable and valuable of building materials.

6. **LOCAL NAMES.**—There is a great variety of names applied to building stones which are derived from the appearance of the stones, from the uses to which they are put, the locality from which they are quarried, etc., which are often very confusing. No classification can be given to cover such nomenclature, and familiarity with local customs can alone enable one to determine the meaning of such names.

7. **ARTIFICIAL STONE.**—There are several kinds of artificial stone which are used for architectural purposes, which are made of combinations of hydraulic cement, sand, gravel, broken stone, etc. No attempt will be made to mention or describe the various patented mixtures.

Concrete, which is rapidly replacing stone-block masonry for many classes of structures, is a mixture of hydraulic cement, sand, and broken stone or gravel. It may be moulded into blocks of any desired shape or used in mass, making the structure a monolith.

The use of concrete usually precludes the need for drawings of separate parts or blocks, but there remains the work of designing the forms and moulds which are needed to give the structure the shape and dimensions desired.

The exposed faces of concrete structures are often made to represent block masonry, and may be given the same finish with tools similar to those later described under stone-cutting tools.

For description of building stones, their chemical and physical properties, durability, cost, etc., and for a full discussion of concrete, see Baker's "Masonry Construction"; "Stones for Building and Decoration," by George P. Merrill.

ART. 2. QUARRYING.

8. Quarrying is an art which can only be acquired by actual experience in the quarries. There are, however, certain facts that the student should be acquainted with if he is to economically plan a masonry structure.

All stones have more or less well defined lines that determine the easiest method of breaking the block from the quarry and which determine the size of the blocks that can be quarried.

In sedimentary rocks (sandstones and limestones) there is a '*bedding*' due to the fact that the sediments were laid down in approximately parallel layers. These stones split easily along planes parallel to the beds, and, if the natural layers are of great thickness, this must be done in quarrying.

There are also in sedimentary rocks two sets of '*joints*' which, with the beds, subdivide the deposit into a more or less regular system of blocks. The set of joints which are approximately perpendicular to the beds and have a general direction with the dip of the rock are called '*dip*' or '*end joints.*' The second set, which are approximately perpendicular to the beds and at right angles to the end joints, are termed '*strike-joints*' or '*back joints.*'

Granite and other eruptive rocks have no beds, but usually show the dip and strike joints and sometimes have '*bottom*' joints which facilitate the quarrying in the same way as do the beds of sedimentary rocks.

9. **Quarrying by Hand-tools.** — Sandstone, limestone, and sometimes granite may occur in thin layers that can be loosened

by the use of hand-tools, without explosives. Stone so thin that it can be quarried by the aid of the pick, bar, and hammer is seldom of a quality fit for buildings.

Stone in layers of considerable thickness can be quarried by the aid of the plug-and-feather method. A line of holes, usually $\frac{3}{4}$ inch in diameter, is drilled along the line desired, and the plugs are inserted between the feathers and driven tightly, care being taken to increase the pressure from the several plugs with uniformity. By this method stones may be broken along lines not coincident with the natural lines of cleavage.

10. **Quarrying by Explosives.**—Usually for quarrying of large stones or in getting out any size of stone from quarries carrying massive rocks, some explosive, coarse gunpowder or low-power dynamite, is used to free the large masses, which are then subdivided by the plug-and-feather method.

The tools used for drilling the holes for the explosive are the *churn-drill*, the *jumper-drill*, and *machine drills*.

The churn-drill is a long heavy drill which is raised by two men, let fall, caught on the rebound, raised, rotated a little, and let fall again, thus cutting by the force of the falling bar, no hammer being used.

The jumper-drill is similar to the hand-drill which is held and struck by one man, except that it is usually larger. It is held by one man, who rotates it slightly between the hammer-blows which are delivered by two men striking in turn.

Machine drills are largely replacing hand-drills in all large quarries. There are two types of machine drill, the percussion and the rotary.

Percussion-drills, driven by steam or compressed air, have a drill attached to the end of a piston-rod, the drill being thrown against the rock by the pressure of the steam or air in the piston. The drill is given a slight rotary motion between the strokes, and is fed down to the work by the attendant by means of a crank and screw.

In rotary drills the drill is forced steadily against the rock, and is revolved about its axis by power. In the *diamond drill* the end of the steel bar may be so set with diamonds that all the material within the circumference of the hole is ground to powder, or the diamonds may be set about the circumference of a hollow

drill, thus cutting an annular space and leaving a core which may be broken off. This drill is much used in prospecting and for the examination of sites for foundations.

Rotary drills with steel cutting-teeth are used in some cases.

Channeling-machines are similar in their action to the percussion drills, and enable a channel to be cut around a block.

Gadding-machines are for the purpose of drilling horizontal holes under a block which may have had a channel cut around it. These holes are used for wedging the block from the quarry. Gadding-machines may be of either the percussion or the rotary type.

11. The product of the quarry is stone, in approximately rectangular blocks, from which all other forms must be wrought by the methods stated in Art. 3, Chap. II. The designer should be familiar with the quarries from which his stock is likely to come, that he may specify sizes that are practical and economical for these quarries to furnish.

See "Stones for Building and Decoration," Merrill; Baker's "Masonry Construction"; Drinker's "Tunneling, Explosives, and Rock-drills."

ART. 3. STONE-CUTTING TOOLS.

12. For a clear understanding of the methods of preparing stones for use it is necessary to describe the tools used.

A committee of the American Society of Civil Engineers prepared a classification of stone-cutting tools, together with definitions of terms used in masonry construction, which have been followed quite generally by engineers and architects. The following is taken from that report.*

"The *Double-face Hammer*, Fig. 1, is a heavy tool weighing from 20 to 30 pounds, used for roughly shaping stones as they come from the quarry and knocking off projections. This is used only for the roughest work.

"The *Face-hammer*, Fig. 2, has one blunt and one cutting end, and is used for the same purpose as the double-face hammer where less weight is required. The cutting end is used for roughly squaring stones, preparatory to the use of finer tools.

"The *Cavil*, Fig. 3, has one blunt and one pyramidal, or

*Trans. A. S. C. E., vol. VI. pp. 297–304.

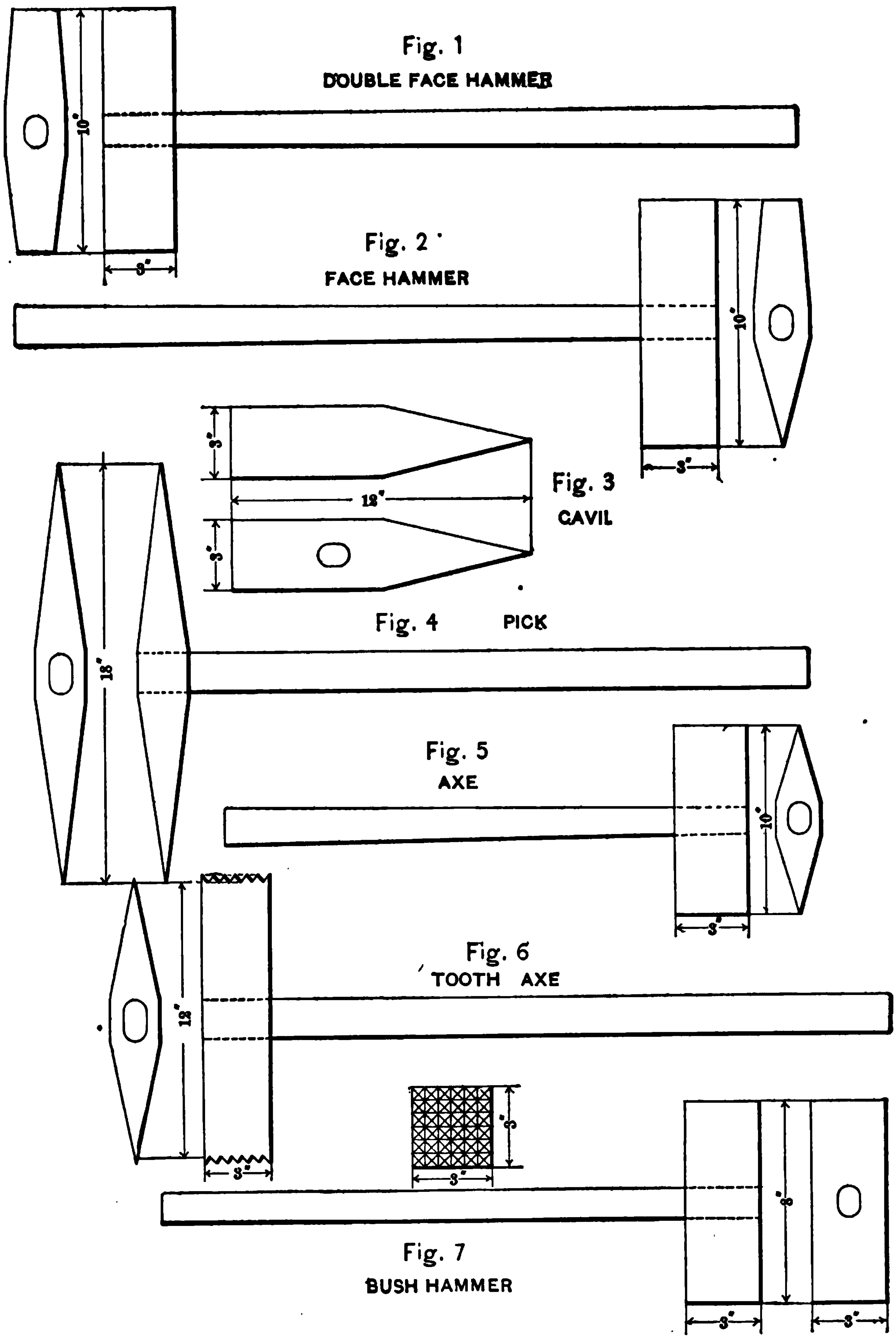


Fig. 1
DOUBLE FACE HAMMER
10"
3"
Fig. 2
FACE HAMMER
10"
3"
Fig. 3
CAVIL
3"
12"
3"
Fig. 4
PICK
18"
Fig. 5
AXE
10"
3"
Fig. 6
TOOTH AXE
12"
3"
3"
3"
Fig. 7
BUSH HAMMER
8"
3"
3"

FIGS. 1-7.

pointed end, and weighs from 15 to 20 pounds. It is used in quarries for roughly shaping stones for transportation.

"The *Pick*, Fig. 4, somewhat resembles the pick used in digging, and is used for rough-dressing, mostly on limestone and sandstone. Its length varies from 15 to 24 inches, the thickness at the eye being about 2 inches.

"The *Axe*, or *Pean-hammer*, Fig. 5, has two opposite cutting edges. It is used for making drafts around the arris, or edge of stones, and in reducing faces, and sometimes joints, to a level. Its length is about 10 inches and the cutting edge about 4 inches. It is used after the point and before the patent hammer.

"The *Tooth-axe*, Fig. 6, is like the axe, except that its cutting edges are divided into teeth, the number of which varies with the kind of work required. This tool is not used on granite and gneiss cutting.

"The *Bush-hammer*, Fig. 7, is a square prism of steel whose ends are cut into a number of pyramidal points. The length of the hammer is from 4 to 8 inches, and the cutting face from 2 to 4 inches square. The points vary in number and size with the work to be done.

"The *Crandall*, Fig. 8, is a malleable-iron bar about two feet long, slightly flattened at one end. In this end is a slot 3 inches long and $\frac{3}{8}$ inch wide. Through this slot are passed ten double-headed points of $\frac{1}{4}$-inch-square steel, 9 inches long, which are held in place by a key.

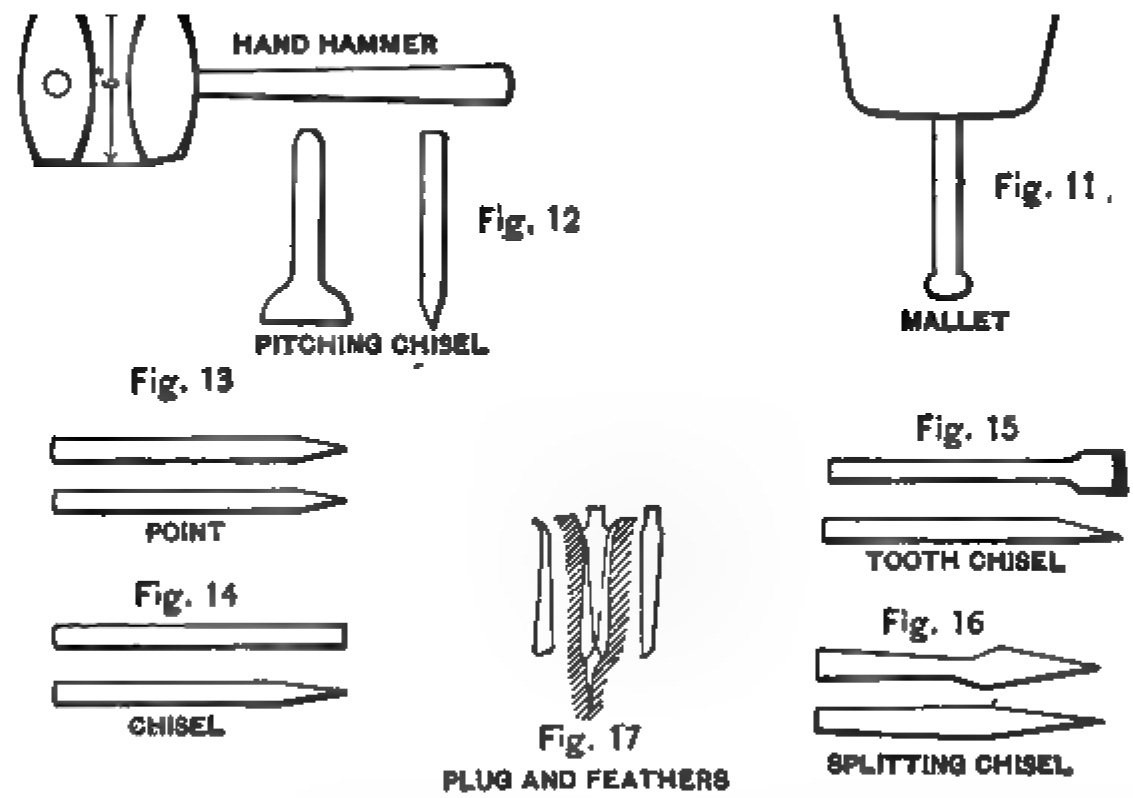
"The *Patent Hammer*, Fig. 9, is a double-headed tool so formed as to hold at each end a set of wide thin chisels. The tool is in two parts which are held together by the bolts which hold the chisels. Lateral motion is prevented by four guards on one of the pieces. The tool without teeth is $5\frac{1}{2} \times 2\frac{3}{4} \times 1\frac{1}{2}$ inches. The teeth are $2\frac{3}{4}$ inches wide. Their thickness varies from $\frac{1}{2}$ to $\frac{1}{6}$ of an inch. This tool is used for giving a finish to the surface of stones.

"The *Hand-hammer*, Fig. 10, weighing from 2 to 5 pounds, is used in drilling holes, and in pointing and chiseling the harder rocks.

"The *Mallet*, Fig. 11, is used where the softer limestones and sandstones are to be cut.

"The *Pitching-chisel*, Fig. 12, is usually of $1\frac{1}{8}$-inch octagonal

steel, spread on the cutting edge to a rectangle of $\frac{1}{8} \times 2\frac{1}{2}$ inches. It is used to make a well-defined edge to the face of a stone, a line being marked on the joint surface to which the chisel is applied, and the portion of the stone outside of the line broken off by a blow with the hand-hammer on the head of the chisel.



Figs. 8–17.

"The *Point*, Fig. 13, is made of round or octagonal rods of steel, from $\frac{1}{2}$ to 1 inch in diameter. It is made about 12 inches long, with one end brought to a point. It is used until its length is reduced to about 5 inches. It is employed for dressing off the irregular surface of stones, either for a permanent finish or pre-

paratory to the use of the axe. According to the hardness of the stone, either the hand-hammer or the mallet is used with it.

"The *Chisel,* Fig. 14, of round steel of $\frac{1}{4}$ to $\frac{3}{4}$ inch in diameter and about 10 inches long, with one end brought to a cutting edge from $\frac{1}{4}$ inch to 2 inches wide, is used for cutting drafts or margins on the face of stones.

"The *Tooth-chisel,* Fig. 14, is the same as the chisel, except that the cutting edge is divided into teeth. It is used only on marbles and sandstones.

"The *Splitting-chisel,* Fig. 16, is used chiefly on the softer stratified stones, and sometimes on fine architectural carvings in granite.

"The *Plug,* a truncated wedge of steel, and the *Feathers,* of half-round malleable iron, Fig. 17, are used in splitting unstratified stone. A row of holes is made with the drill, Fig. 18, on the line on which the fracture is to be made; in each of these holes two feathers are inserted, and the plugs are driven in between them. The plugs are then gradually driven home by light blows of the hand-hammer on each in succession until the stone splits."

There is a great variety of *Machine Tools,* stone-saws, stone-cutters, stone-planers, stone-grinders, and stone-polishers now in use for cutting and finishing stones. As the classification of masonry and the kinds of finish are usually based upon the methods of working with hand-tools, no description of these machine tools is necessary in this place.

Art. 4. Method of Finishing the Surfaces.*

13. "All stones used in building are divided into three classes, according to the finish of the surface, viz.:

I. Rough stones that are used as they come from the quarry.
II. Stones roughly squared and dressed.
III. Stones accurately squared and finely dressed.

"In practice the line of separation between them is not very distinctly marked, but one class merges into the next.

14. I. "**UNSQUARED STONES.**—This class covers all stones which are used as they come from the quarry, without other preparation than the removal of very acute angles and excessive

* Trans. Am. Soc. C. E., vol. vi. pp. 297-304.

projections from the figure. The term 'backing,' which is frequently applied to this class of stone, is inappropriate, as it properly designates material used in a certain relative position in the wall, whereas stones of this kind may be used in any position.

15. II. "**SQUARED STONES.**—This class covers all stones that are roughly squared and roughly dressed on beds and joints. The dressing is usually done with the face-hammer or axe, or in soft stones with the tooth-hammer. In gneiss it may sometimes be necessary to use the point. The distinction between this class and the third lies in the degree of closeness of the joints. Where the dressing on the joints is such that the distance between the general planes of the surfaces of adjoining stones is one-half inch or more, the stones properly belong to this class.

"Three subdivisions of this class may be made, depending on the character of the face of the stones:

"(*a*) **Quarry-faced** stones are those whose faces are left untouched as they come from the quarry. (Fig. 18.)

"(*b*) **Pitch-faced** stones are those on which the arris is clearly defined by a line beyond which the rock is cut away by the pitching-chisel, so as to give edges that are approximately true.

"(*c*) **Drafted Stones** are those on which the face is surrounded by a chisel-draft, the space within the draft being left rough. Ordinarily, however, this is done only on stones in which the cutting of the joints is such as to exclude them from this class.

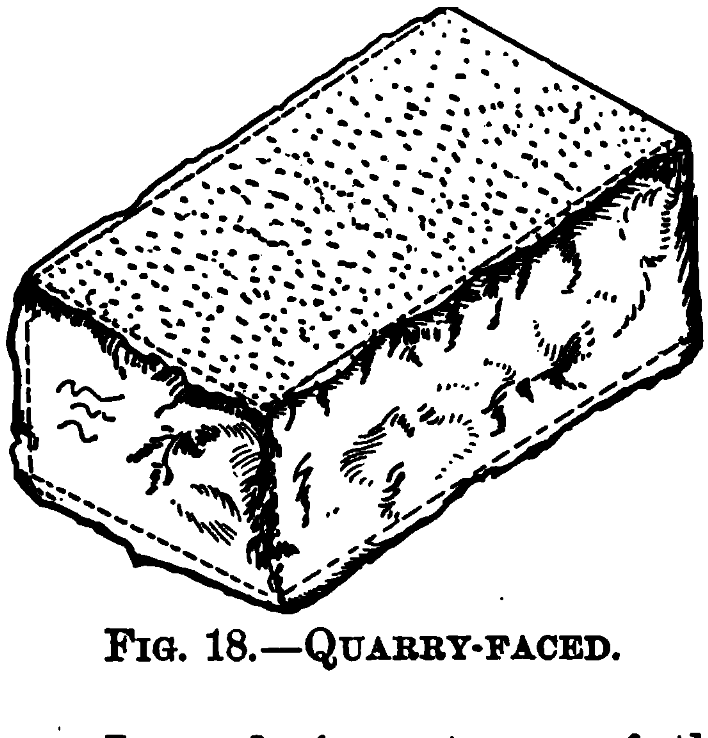


FIG. 18.—QUARRY-FACED.

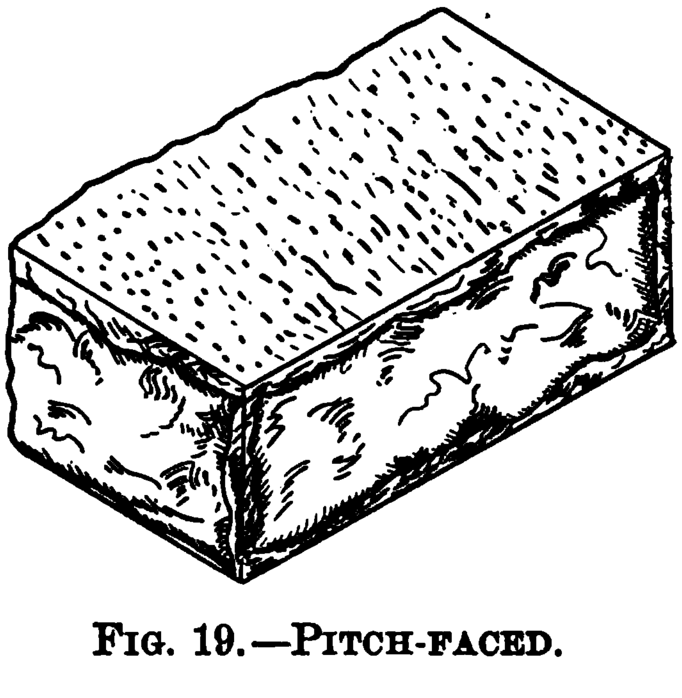


FIG. 19.—PITCH-FACED.

"In ordering stones of this class the specifications should always state the width of the bed and end joints which are expected, and also how far the surface of the face may project beyond

the plane of the edge. In practice the projection varies from 1 inch to 6 inches. It should also be specified whether or not the faces are to be drafted.

FIG. 20.—DRAFTED STONE.

16. III. "CUT STONES.—This class covers all squared stones with smoothly dressed beds and joints. As a rule all the edges of cut stones are drafted, and between the drafts the stone is smoothly dressed. The face, however, is often left rough where the construction is massive.

"In architecture there are a great many ways in which the faces of cut stone may be dressed, but the following are those which will usually be met in engineering work:

"**Rough-pointed.**—When it is necessary to remove an inch or more from the face of a stone, it is done by the pick or heavy point until the projections vary from ½ inch to 1 inch. The stone is then said to be rough-pointed (Fig. 21).

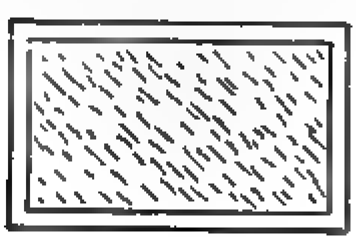


FIG. 21.—ROUGH-POINTED.

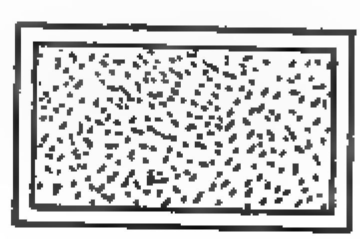


FIG. 22.—FINE-POINTED.

"**Fine-pointed** (Fig. 22).—If a smoother finish is desired, rough-pointing is followed by fine-pointing, which is done with a fine point. Fine-pointing is used only where the finish made by it is to be final, and never as a preparation for a final finish by another tool.

"**Crandalled.**—This is only a speedy method of pointing, the effect being the same as fine-pointing, except that the dots on the stone are more regular. The variations of level are about $\frac{1}{8}$ inch, and the rows are made parallel. When other rows at right angles to the first are introduced, the stone is said to be cross-crandalled (Fig. 23).

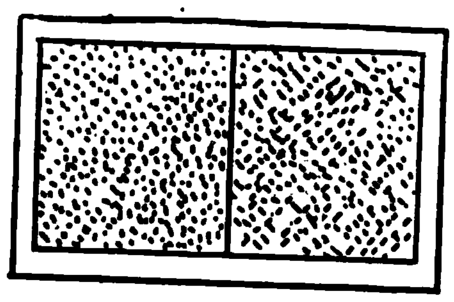


FIG. 23.—CRANDALLED.

"**Axed,** or **Pean-hammered,** and **Patent-hammered.**—These two vary only in the degree of smoothness of the surface which is produced. The number of blades in a patent hammer varies from 6 to 12 to the inch; and in precise specifications the number of cuts to the inch must be stated, such as *6-cut, 8-cut, 10-cut, 12-cut.* The effect of axing is to cover the surface with chisel-marks, which are made parallel as far as practicable. (Fig. 24.) Axing is a final finish.

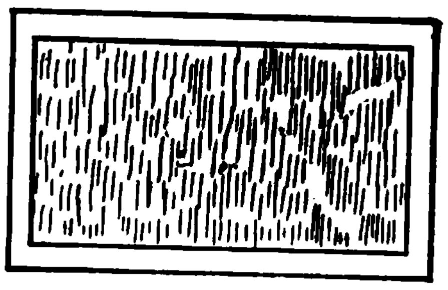


FIG. 24.—AXED.

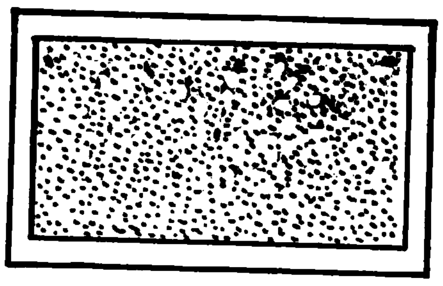


FIG. 25.—BUSH-HAMMERED.

"**Tooth-axed.**—The tooth-axe is practically a number of points and leaves the surface of the stone in the same condition as fine-pointing. It is usually, however, only a preparation for bush-hammering, and the work is done without regard to effect so long as the surface of the stone is sufficiently leveled.

"**Bush-hammered.**—The roughness of the stone is pounded off by the bush-hammer, and the stone is then said to be 'bushed.' This kind of finish is dangerous on sandstone, as experience has shown that sandstone thus treated is very apt to scale. In dressing limestone which is to have a bush-hammered finish, the usual sequence of operations is (1) rough-pointing, (2) tooth-axing, and (3) bush-hammering (Fig. 25).

"**Rubbed.**—In dressing sandstone and marble, it is very common to give the stone a plane surface at once by the use of the stone-saw (§ 12). Any roughnesses left by the saw are removed

by rubbing with grit or sandstone. Such stones, therefore, have no margins. They are frequently used in architecture for string-courses, lintels, door-jambs, etc.; and they are also well adapted for use in facing the walls of lock-chambers, and in other locations where a stone surface is liable to be rubbed by vessels or other moving bodies.

"**Diamond Panels.**—Sometimes the space between the margins is sunk immediately adjoining them, and then rises gradually until the four planes form an apex at the middle of the panel. In general such panels are called diamond panels, and the one just described (Fig. 26) is called a sunk diamond panel. When the surface of the stone rises gradually from the inner lines of the margins to the middle of the panel, it is called a raised diamond panel. Both kinds of finish are common on bridge-quoins and similar work. The details of this method should be given in the specifications."

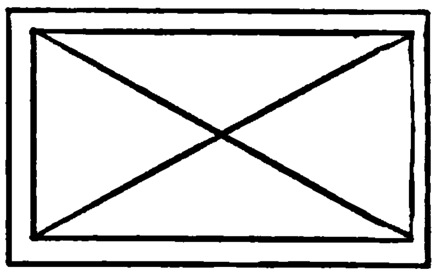


FIG. 26.—DIAMOND PANEL.

ART. 5. DEFINITIONS OF PARTS OF THE STRUCTURE.

17. *Face,* the front surface of a wall; *back,* the inside surface.

Facing, the stones which form the face, front, or outside of the wall, often of a higher grade of workmanship than the body of the wall.

Backing, the stones which form the back of the wall.

Filling, the interior of the wall. The term backing often covers all the stone in the wall except the facing.

Batter, the inclination of the wall from a vertical plane, commonly stated as so many inches to the foot. A batter of 2 inches to 1 foot means that for 1 foot vertical rise of the wall its face recedes 2 inches horizontally from the vertical plane.

Slope. When the surface of masonry is greatly inclined, as in some pavings on wave-washed structures, and when the inclination of earthwork is spoken of, the slope is given by the ratio of the horizontal to the vertical departure of one point on the surface from a point below it. Thus a slope of 1½ to 1 signifies an incline such that in the vertical distance of one unit the surface departs 1½ units from the vertical plane.

A slope of $1\frac{1}{2}$ to 1 is equivalent to a batter of 18 inches to the foot.

Course, a horizontal layer of stones in the structure.

Joints, the mortar-layer between the stones. The horizontal joints are called *bed-joints,* or simply *beds.* The vertical joints are sometimes called *builds.* Usually the horizontal joints are called *beds,* and the vertical ones *joints.*

Coping, a course of stone on top of the wall to protect it from the weather. The coping may be 'weathered' (the top surface cut on an incline so as to drain water from its surface.)

Pointing, a better quality of mortar than is used in the body of the work, which is used in the face of the joints to protect the wall from the weather.

Bond, the arrangement of the stones in adjacent courses for the purpose of tieing the parts of the wall together.

Stretcher, a stone whose greatest dimension lies parallel to the face of the wall.

Header, a stone whose greatest dimension lies perpendicular to the face of the wall.

Quoin, a corner-stone. A quoin is a header for one face and a stretcher for the other.

Lintel, a stone used to support a wall over an opening.

Dowels, straight bars of iron or steel which enter a hole in the upper surface of one stone and also a hole in the lower surface of the stone next above.

Cramps, bars of iron or steel having the ends turned at right angles to the body of the bar, which enter holes in the upper sides of adjacent stones.

Art. 6. Classification of Masonry.

18. "**Masonry** in its widest sense includes all constructions of stone or kindred substitute materials in which the separate pieces are either carefully placed together, with or without cementing material to join them, or, if the pieces are not separately placed with care, are encased in a matrix of firmly cementing material."

19. **Stone masonry** includes all classes of construction in which separate stones are skillfully assembled, either with or without mortar, into structures of required form and dimensions.

20. Rubble Masonry.—This is composed of unsquared stones which may be laid without any attempt at coursing, forming *uncoursed rubble*, or the work may be evened up at certain heights, forming *coursed rubble.* (Figs. 27, 28.)

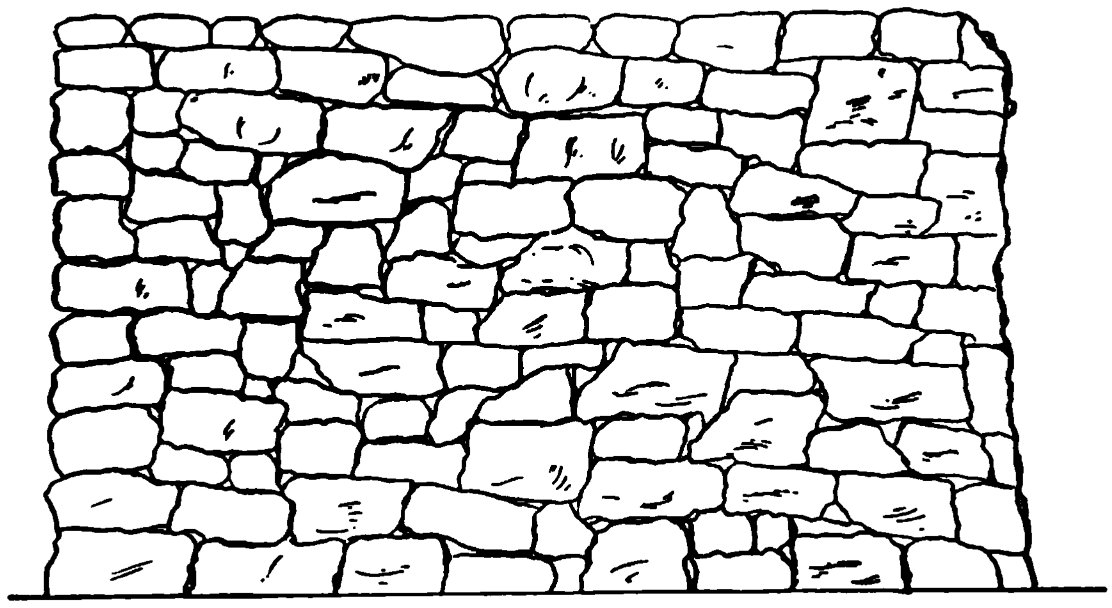


FIG. 27.—UNCOURSED RUBBLE.

Sandstone and limestone, which occur in the quarry in relatively thin layers, are frequently trimmed with the face-hammer into approximately rectangular pieces, and when laid have the appearance of squared-stone masonry. Such work is sometimes called squared rubble, but might well be classed in the next order.

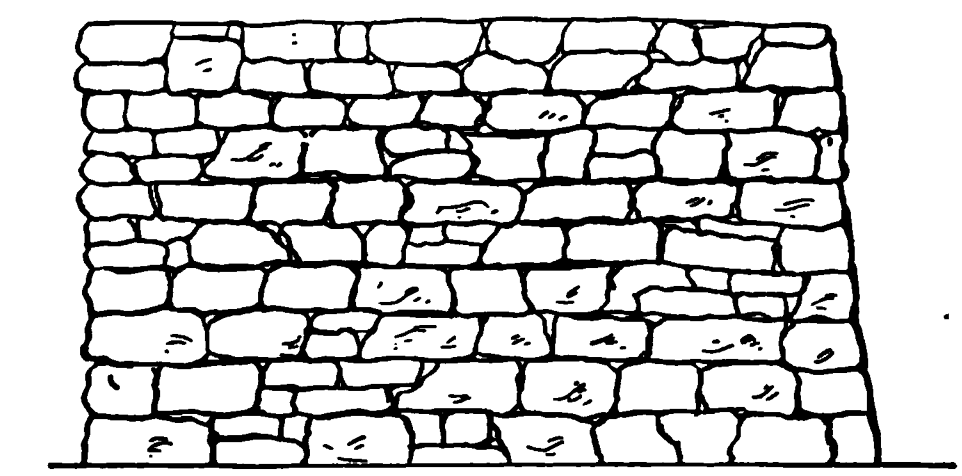


FIG. 28.—COURSED RUBBLE.

21. Squared-stone Masonry.—Work in which the joints are dressed so that the adjacent stones will lay with joints of over $\frac{1}{2}$ inch, and in which the general outline of the stone is rectangular. This class runs into the next.

The faces may be quarry-faced or pitch-faced (§ 15).

If laid in regular courses of about the same height throughout, it is termed '*Range-work*'; if the courses are not continuous, it is '*Broken Range-work*'; and if not laid in courses at all, it is '*Random-work.*'

22. Ashlar.—According to the report of the committee of the American Society of Civil Engineers, "when the dressing of the joints is such that the distance between the general planes of the

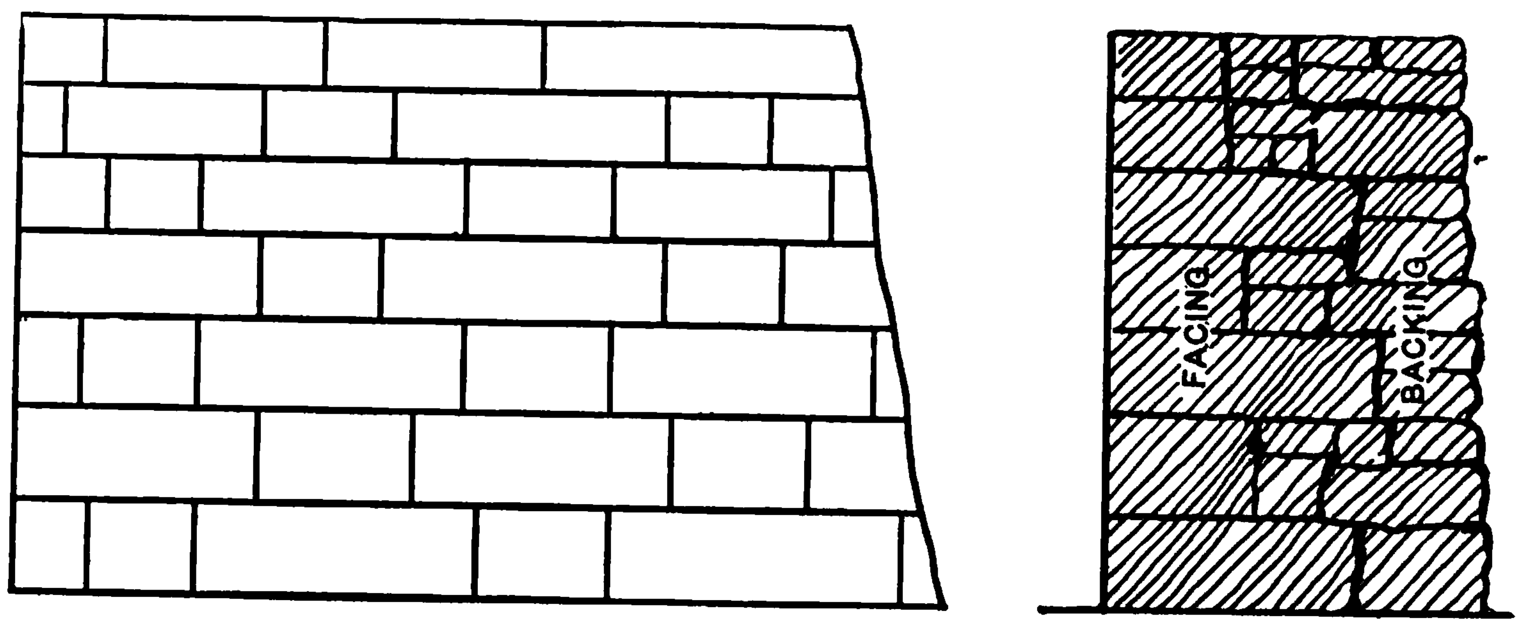


FIG. 29.—RANGE.

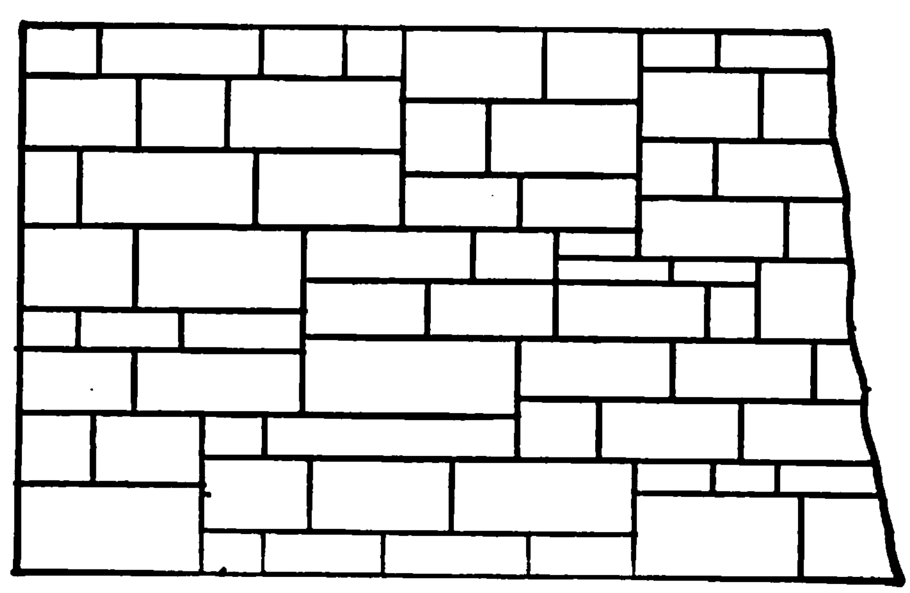


FIG. 30.—BROKEN RANGE.

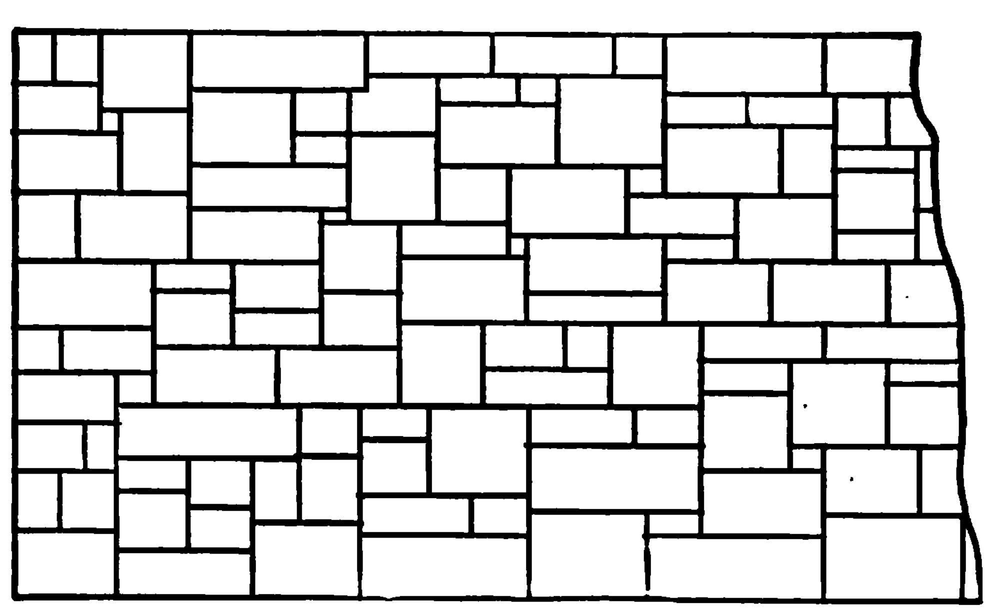


FIG. 31.—RANDOM.

surfaces of adjacent stones is one-half inch or less, the masonry belongs to this class." The term ashlar as generally used is synonymous with '*cut stone.*' The faces may have any of the

finishes mentioned in Art. 4, and the arrangement of the stones in the wall may be the range, broken range, or random, as described in § 21.

23. In railroad construction masonry is generally classified as **First-, Second-, or Third-class Masonry.** The character of the stonework in these classes is practically like the ashlar, squared stone, and rubble just described. (See Art. 7.)

Art. 7. General Rules and Specifications.

24. **General Rules.**—The following rules are given by Rankine:

"I. Build the masonry, as far as possible, in a series of courses, perpendicular, or as nearly perpendicular as possible, to the direction of the pressure which they have to bear; and avoid all long continuous joints parallel to that pressure by 'breaking joints.'

"II. Use the largest stones for the foundation course.

"III. Lay all stones which consist of layers or 'beds' in such a manner that the principal pressure which they have to bear shall act in a direction perpendicular, or as nearly perpendicular as possible, to the direction of the layers. This is called 'laying the stone on its natural bed,' and is of primary importance to strength and durability.

"IV. Moisten the surface of dry and porous stones before bedding them, in order that the mortar may not be dried too fast, and reduced to powder by the stone absorbing its moisture.

"V. Fill every part of every joint, and all spaces between the stones, with mortar; taking care at the same time that such spaces shall be as small as possible."

25. **ASHLAR MASONRY.**—Size of stones. To provide the proper strength of the stones it is usual to specify the length and breadth of the stones in terms of the depth. For the softer stones the length should not exceed 3 times the depth, nor the breadth $1\frac{1}{2}$ to 2 times the depth. In harder stones the length may be 4 or 5 times the depth, and the breadth 3 times the depth.

26. **Dressing.**—The face may be finished in any one of the various ways described in Art. 4, and the beds and joints vary with the character of the work. In the finest of building work, as, for example, the U. S. public buildings, the joints are about $\frac{1}{8}$ inch. In engineering structures, such as piers, bridges, docks, etc., the joints are usually from $\frac{1}{4}$ to $\frac{1}{2}$ inch.

It is not desirable to have the joints smooth in any case, but to have the projections reduced to a general plane. An *open joint* is caused by the failure to reduce some of the projections and thereby preventing the stones from coming to the desired joint. Such a joint is very objectionable in the beds, for it causes the pressure to be concentrated on points rather than evenly over the bed. *Flushed joints* are those in which the surface of the stone has been hollowed. This is sometimes purposely done, to enable the mason to obtain a fine joint on the exterior of the work, with less careful labor than would be necessary to properly dress the stone. Flushed joints are also very objectionable, for the pressure is then concentrated on the edges of the stone.

27. **Bond.**—No side-joint of any course should be directly above a side-joint in the course below; but the stones should overlap, or break joints, to an extent of from 1 to $1\frac{1}{2}$ times the depth of the course.

The strongest bond is that in which each course is made up of alternate headers and stretchers, the header of one course resting on the middle of the stretcher of the course below. Such a bond would cause about one third of the face of the wall to be composed of headers.

Blind headers are sometimes used by dishonest masons. Blind headers present the same appearance in the finished wall as the true headers, but are of no use in binding the wall together.

Dowels and cramps may be used in structures requiring great strength, as in bridge piers subject to great lateral forces.

28. **Backing.**—Ashlar is usually backed with rubble masonry (brick is also much used in architectural work), which is laid in courses of the same depth as the ashlar. The ashlar face and the backing are bonded together by the headers which extend from the ashlar into the backing. The end of the header which enters the backing, "the tail," should maintain its thickness throughout, but may taper slightly in breadth. Headers from the backing should project from the backing into the spaces between the headers of the ashlar. When the wall is less than 5 feet thick it is common to require the headers to extend through the wall.

29. **Pointing.**—After the completion of the work the mortar is raked out of the face-joints to the depth of from 1 to 2 inches, and the space filled with a high-grade mortar. Portland cement, clear

or mixed with equal volumes of sand, is frequently used for pointing.

30. **SQUARED-STONE MASONRY.**—The same general specifications that were gixen in §§ 25, 27 will apply to this class of masonry, the only distinction between the two classes being the fineness of the finish and the closeness of the joints.

31. **RUBBLE MASONRY.**—The stones used for rubble masonry should have the weak angles knocked off, should be cleaned, and moistened before being laid. *Dry rubble* is laid without mortar for some unimportant work. Its use is becoming rare in engineering works. Rubble laid in mortar should be well bonded, vertically by breaking joints and horizontally by headers. Much skill is required to obtain good rubble masonry, especially if the stones are very irregular.

Rubble masonry is frequently used in foundations, for small bridge abutments, culverts, and for backing.

32. The following specifications are recommended by the Committee of the American Railway Engineering and Maintenance-of-way Association, March, 1902:

33. "**Description of Stone Masonry.**—All stones used for masonry shall be sound, durable, not liable to be affected by the weather, from sources approved by the engineer, and shall be laid on their natural beds.

34. "*Mortar* for laying up stone masonry, unless otherwise expressly stated, shall consist as follows:

"Either 1 part of approved Portland cement to 4 parts of good sharp sand, or 1 part of approved natural cement to 2 parts good sharp sand, all to be very carefully measured and mixed, and to be used within one hour after mixing, and always before it shall have commenced to set.

"Mortar for pointing shall consist of 1 part Portland cement to 1 or 2 parts of sand.

35. "*Finishing Copings, Parapets, Bridge-seats, and other Finely Dressed Special Stones.*—Work that comes under this head shall be of selected stone, of the best quality, free from defects, shall be very accurately cut, being bush-hammered where called for, and as per plan and dimensions given. To be laid to $\frac{3}{8}$-inch joints.

36. "**First-class Masonry.**—First-class masonry shall be laid in Portland-cement mortar, in regular courses, each stone being

carefully cleaned and dampened, if desirable, before setting. The face-stones shall be rock-faced, with edges pitched to a straight line (pitch-faced), and no projections exceeding 3 inches. A draft-line, 2 inches wide, shall be cut at each angle in the masonry. The beds throughout and the joints for 12 inches back from the face shall be dressed to lay to $\frac{1}{2}$-inch joints. No course shall be less than 12 nor more than 30 inches in thickness, and the thickness of any course shall not exceed the course below it. *Stretchers* shall not be less than 3 feet long and not less than 18 inches wide, nor less in average width than $1\frac{1}{4}$ times the height, and at no single place less in width than the height.

37. "*Headers* must not be less than 4 feet long, where the wall is of sufficient thickness, and the majority shall exceed that length. Where the wall is not over 5 feet thick, they shall extend entirely through the wall. Headers will extend at least 20 inches beyond the width of the adjacent stretchers. The usual arrangement shall consist of headers and stretchers, alternately arranged, so as to thoroughly bond together the face-stones and the backing; for rare exceptions two stretchers will be allowed to one header, by special permission, to cover each such case. The stones of each course of the face must break joints at least 1 foot with those of the course below. No hammering will be allowed on any stone after it is set. Each stone must be set upon a full bed of fresh mortar, the broadest bed down, and brought to a firm and level bearing without spalls or pinners.

38. "*Backing.*—The backing shall consist of large-sized, well-shaped stones laid in full mortar beds, and breaking joints so as to thoroughly bond the work together. The spaces between the larger stones shall not be over 6 inches in width, and shall be thoroughly filled with small stones and spalls laid flat, and the spaces flushed with mortar. The courses shall correspond with the face-stone, but may be made up in part by two thicknesses, providing no stone less than 8 inches thick be used. In cases approved by the engineer, satisfactory Portland-cement concrete may be used for backing.

39. "**Second-class Masonry.**—Second-class masonry shall be laid in cement mortar. The face-stones shall be rock-faced, no projections over 3 inches, edges pitched to a straight line, shall have parallel beds and rectangular joints. The beds and joints

for 8 inches back from the face shall be dressed to lay not over $\frac{3}{4}$-inch joints. The stones need not be laid up in regular course, but shall be laid level on their natural beds, shall be well bonded, having at least one header 3 feet 6 inches long to every three stretchers, with joints well broken; no stone shall be less than 8 inches thick, and no stone shall measure in its least horizontal dimensions less than 12 inches, nor less than its thickness.

40. "*Backing.*—The backing shall consist of well-shaped stones, not less than 6 inches thick, and of which at least half shall measure 3 cubic feet, to be laid in full mortar beds, with joints well broken, well bonded together, and with the face-stone. All spaces to be thoroughly filled with small stones and cement mortar.

41. "**Third-class Masonry.**—Third-class masonry shall be laid dry or in mortar, acccording to the direction of the engineer. It shall consist of good quarry stone, laid upon the natural beds, and roughly squared on the joints, beds, and faces, the stones breaking joints at least 6 inches; the wall shall be bound together by headers, occupying one fifth of the area of the face of the wall, front and rear, and extending through walls 3 feet or less in thickness; no stone shall be used in the face of the wall less than 6 inches thick, or less than 12 inches on the least horizontal dimensions."

CHAPTER II.

STONE-CUTTING.

ART. 1. DEFINITIONS.

42. **Stereotomy,** as applied to stone-cutting, consists of cutting stones from the rough blocks so that when fitted together they will form a predetermined whole. It consists of three distinct parts: first, the constructions of the projections of the structure on as large a scale as convenient; second, the proper division of the structure into blocks and the obtaining of the directing instruments used to cut the blocks; third, the proper order of the application of the directing instruments to obtain the best results.

43. Structures may be classified by the character of the surfaces as follows: first, those having *plane surfaces* only; second, those having *developable surfaces;* third, those having *warped surfaces;* fourth, those having *surface of double curvature.* No sharp division in the order of treating these different classes has been made in this book.

ART. 2. REMARKS ON PREPARATION OF DRAWINGS.

44. The drawings usually prepared by the engineer or architect for masonry structures vary with the character of the structure and the class of work desired. The drawings may be so complete and in such detail that the figured dimensions of every stone are shown, or the drawing may simply give the outlines and dimensions of the finished structure, allowing the size, shape, and arrangement of the individual stones to be determined by the masons, and limiting them only by the specifications.

Between these two extremes there may be drawings which, besides showing the structure, give dimensions of certain stones, courses, or other parts which are to be cut work.

It is well to bear in mind the fact that the quarry product is a variety of roughly rectangular blocks differing in size, and that often these blocks can be built into a strong and pleasing structure by a slight reduction in the size of the blocks due to the dressing. Should arbitrary dimensions be given to the stones, it may often happen that there will be much waste of material and labor, with no resulting advantage. It is not unusual to state the heights of the courses and allow the mason to vary the linear dimensions of the stones in such a way as to preserve the desired bond, fill out the total dimension of the structure, and at the same time economically use the product of the quarry.

In rubble work of course no dimensions are given for any stones. Squared-stone masonry and ashlar, when laid as broken range or random, are not usually shown with dimensions for each block, although in some architectural work such dimensions are given.

45. **Drawings of the Structure.**—There should be a sufficient number of drawings to clearly show all the dimensions of the structure, and such figured dimensions should be given as will permit of a reproduction of the structure which the designer has in mind, full size, in solid stone, without the necessity of scaling from the paper.

The Plan, or horizontal projection, should show the controlling horizontal surface. In many engineering works the top or upper surface is chosen, the dimensions of other horizontal planes being determined by the batter of the side surfaces. This is convenient for piers, abutments, walls, etc., the depth to which they must go being often uncertain until the excavation for the foundation is completed.

Sectional Plans, or horizontal sections, may be needed when the structure abruptly changes its shape.

Elevations, or side views, or vertical projections should show the dimensions of lines which are projected in their true length.

Sections should show the dimensions of the structure where the cutting planes are supposed to be taken. When a drawing shows part section and part elevation it is well to section-line the section or distinguish it from the elevation portion of the drawing.

46. **Drawings of Individual Stones.**—Having completed the drawings of the structure, there remains the work of determining

the size, shape, and arrangement of the blocks that are to compose it.

Plane structures, such as walls, piers, buildings, etc., having no difficult stones to cut, may have the dimensions of the stones shown directly upon the plans and elevations, or the stones may be numbered upon the general or key drawings, and a detail drawing of each different shape be referred to by these numbers. (See Plates IV, V, VI, VII, XII, and XIII.)

Structures having curved or warped surfaces must have the shape and dimensions of the stones composing it, properly worked out. Methods will be developed in the following chapters for the finding of the projections, developments, shapes, and sizes of such stones. In many of the problems the dimensions may be found by simple calculations, and where this is true the calculations should be made. A thorough understanding of the descriptive geometry of the problems will enable the student to calculate the length of lines, sizes of angles, etc., which he has projected. If the problem is not easily calculated, it will be necessary to depend upon the graphical constructions. These are often made to a small scale by the engineer or architect, and later reproduced to large or full scale by the stone-cutter.

The student is cautioned against placing upon the drawing any dimension which he has obtained by scaling. If such dimension is written, it implies that it is exact. If it is omitted, it will generally be supplied by the laying out of the work to full size.

For directions for properly placing dimensions upon drawings the student should thoughtfully study the drawings prepared by experienced draftsmen, some examples of which will be found on Plates IV, V, VI, VII, XIX, XX, etc.

Art. 3. Methods of Cutting Stones. Directing Instruments.

47. Forming of Plane Surfaces.—To reduce the face of a rough block of stone to a plane, a straight line along one edge is marked and a draft cut to this line, testing by the straight-edge.

Having the first draft-line, a second is worked down on the opposite side of the surface. To prevent a wind in the surface, two straight-edges having the same width are placed on the two drafts and the drafts corrected until the top edges of the *parallel*

rules lie in the same plane, which is readily tested by placing the eye on the same level as the tops of the rules and at a short distance from them, and sighting over them. If there is no wind in the drafts, that is, if they lie in the same plane, the two edges will appear to coincide. Having the two drafts properly cut, the end drafts may be cut down until they are in line with the straight-edge applied between the ends of the first drafts. The surface between the four draft-lines may now be pitched down till the straight-edge touches the surface at all points along its edge, in any position in which it is placed. If the side surfaces are to be planes, they are worked as follows: Having the bed or top surface of the stone worked to a plane, and its outlines marked upon it by the *pattern* (which may be of zinc, iron, or thin wood, cut to the figure required), draft-lines are cut on the side surfaces, perpendicular to the edge common to the side and top, and at the proper dihedral angle. The dihedral angle between the top and side surface is determined by the application of a *bevel*, formed by two straight-edges framed together, or the angle may be cut from metal or wood. If the angle is 90°, the bevel is called a *square*. Having two draft-lines, as far apart as possible, sunk in the side surface so that they are straight and make the proper angle with the first surface, the side surface is completed by working to the drafts with the straight-edge, as in the case of the first surface. Patterns of the side surfaces determine the end lines for these surfaces. All the sides and the two beds having been correctly worked, the ends may be cut to the end lines of these surfaces. Patterns of the end surfaces may be applied as a check on the work. They should fit if the beds and sides have been accurately worked as above described. Fig. 32 shows a rectangular block with the parallel rules, and square in position for one draft of the side surface. One blade of the square here serves as one of the parallel rules. The side and end show a draft around these surfaces, with the area between the drafts left in rock face. In the case of such rock faces patterns cannot be applied to the surfaces, but the direction of the end lines is obtained by bevels or square, giving the face-angles of the surface.

48 Cylindrical Surfaces, either concave or convex, may be formed in a way similar to that employed for plane surfaces, except that, in place of the parallel rules, two rules may be used, each of

which has one straight-edge, and the second edge of each cut to the proper arc. A straight-edge connecting two drafts sunk with these rules, or templates, determine the surface.

Another method is to cut two straight drafts with the straight-edge and parallel rules, and then work out the cylindrical surface

Fig. 32.

between the drafts, testing with a *template* cut to the proper radius.

To work a plane surface from a cylindrical surface, or *vice versa*, an *arch square* in place of a bevel or simple square is used. The arch square has one arm of the square cut to fit the cylindrical surface, and the second arm a straight-edge framed to the first at the proper angle, usually normal to the arc.

Fig. 33 shows a cylindrical surface with templates on the end drafts, and the arch square placed to test one side surface.

49. A Conical Surface may be cut in a manner similar to that described for a cylindrical surface, replacing the equal-end templates by templates cut to the radius of the cone at the planes where the drafts are to be cut.

50. Spherical Surfaces are tested by templates cut to the radius of the sphere on which the surface is located.

51. Warped Surfaces having two straight lines for directrices, are formed by sinking drafts to correspond to the directrices and applying the straight-edge to these drafts. To sink the drafts *twisting rules* are used. The first rule has its two edges

parallel; the second has its edges diverging, the height at one end of the rule equaling the height of rule number one, and the other end wider than the first, the amount depending on the amount of twist in the surface. The drafts are correct when the upper edges of the twisting rules are in a plane, this being determined by sighting as described in the case of the parallel rules on plane

FIG. 33.

surfaces. Fig. 34 shows a warped surface with the twisting rules in place. The wires connecting the rules are to keep them at the right distance apart, and are used in some cases.

ART. 4. MODELS IN PLASTER.

52. A valuable exercise in connection with the study of the various problems presented in the following chapters is to cut from blocks of plaster some of the stones called for by the drawings. It may not be desirable for the student to work out many such blocks. If two or three are selected which will illustrate the uses of patterns, templates, squares, bevels, and twisting rules, they will serve to awaken interest and original thought in the student.

Figs. 32–35 are from photographs of models cut from plaster to a scale of 1 inch to 1 foot.

A few simple directions may aid the student in such work. To prepare a block from which to cut the desired stone, take any box or dish having some batter to its sides to permit of drawing

Fig. 34.

the block when it becomes solid, grease the sides with lard and put into it equal parts, by weight, of plaster of Paris and water. Stir well and then allow to set. In a half-hour the solid block may be removed. If a large number of blocks are to be prepared, simple moulds made of planed wood may be easily constructed. If a few blocks are to be made, boxes of pasteboard may be used. Old crayon-boxes, which may be pulled to pieces after the plaster is set, were used for the blocks shown in the figures. Large blocks may be subdivided into blocks of approximately the desired size by the use of an old saw. Mixed of equal parts of plaster and water the block is quite hard and cuts with a little more difficulty than a mixture containing a greater percentage of water. However, the exact proportions are of little moment.

Having the rough block, the process of cutting any desired stone should be proceeded with in exactly the same order as would

be followed by the stone-cutter working the same stone from granite.

Straight-edges, squares, bevels, patterns, and templates may be constructed of thin wood or cut from pasteboard. The only tool necessary is a sharp knife, although chisels and a metal straight-edge may be useful.

53. **Casting.**—If it is desired to make a number of duplicates of any stone, as, for example, to make all the stones composing one zone of the dome, casts may be made. Having one stone carefully cut to required shape, thoroughly grease all its surface, and, placing

FIG. 35.

it in a box, pour around it plaster and water until the liquid rises to the level upon which the mould is to be parted. Allow this plaster to set, then grease the surface of the plaster and pour in enough liquid to cover the pattern to a fair thickness. After this plaster has set, the mould may be parted and the original pattern taken out.

There is now a cavity formed by the two halves of the mould, which, if poured full of plaster, will produce a duplicate of the original block. The mould must be well greased before each cast

is made. If the mould has become thoroughly dry, it is well to wet it before casting. Some thought must be given to the way in which the mould should be parted, or the block cannot be drawn from the mould. (Fig. 35.) The mould should have a hole cut into it at some high point in the upper half through which to pour the plaster. Make this hole quite large, and use very thin plaster mixture. Shake the mould well, to aid the liquid to reach all parts of the mould and for the air to escape.

CHAPTER III.

PLANE SIDED STRUCTURES.

ART. 1. NOTATION.

54. The horizontal and vertical planes of projection are, for the sake of brevity, denoted by their usual symbols, **H** and **V**.

In order to aid the student in reading the proof of the different problems, as far as possible a uniform notation is used; points in **V** are represented by primes (as A′); those in **H** by plain letters, or letters with subscripts (as A, A_1, A_2, etc.); points in their revolved position are designated by seconds, thirds, etc. (as A″, A‴, etc.). Thus we know at once on what part of the drawing a desired point is to be found.

The usual rules for inking visible and invisible lines are followed. In a few cases, however, greater clearness may result by viewing a structure vertically upwards from below. Invisible lines should be distinguished from construction lines by the length of the dash. This distinction is not shown, however, in the plates of this book. The terms 'plan' and 'horizontal projection' are used interchangeably in the work, and also 'elevation' and 'vertical projection.'

ART. 2. THE BUTTRESS.

PLATE I. FIG. 1.

55. **Problem.**—A wall with its front face inclined. In front of and forming a part of this wall is a buttress. The base of the buttress is in the same horizontal plane as the base of the wall; the faces and top of the buttress have given slopes.

Let the wall be 20 ft. high, 9 ft. thick at the base, with a batter of 2 in. to 1 ft. on its front, and its back face vertical; let the height of the buttress at its junction with the main wall be 16 ft.

4 in., the slope of its front face 3 in. to 1 ft., that of its side faces 2 in. to 1 ft., and that of its top 72 in. to 1 ft.; the perpendicular distance from the foot of the main wall to the foot of the buttress = 4 ft., and the width of the buttress at foot of main wall = 8 ft. The other dimensions of the buttress will be given below.

56. The Projections.—First, construct a cross-section of the main wall and buttress, taken through the center of the buttress on the line UV. Make $E''E''' = 20$ ft., $A''E''' = 9$ ft., and $A''m = \frac{1}{6} E''E'''$; $A''G'' = 4$ ft.; and from G'' draw $G''a''$ with a batter of 3 in. to 1 ft., till it intersects $c''a''$, drawn with a batter of 72 in. to 1 ft., the point c'' being 16 ft. 4 in. above $A''E'''$.

Second, the construction of the plan and front elevation is obvious from the drawing. All the heights in elevation are determined by projecting across from the section; the widths in plan by transferring the horizontal distances $E''C''$, $E'''A''$, etc., from the section to any line, as ij, perpendicular to EF or the groundline. The other dimensions are given, as GH = 5 ft., IJ = 8 ft., and the perpendicular distance from IJ to GH = 4 ft.

Then it is necessary to find the horizontal and vertical projections of the intersection of the main wall with the side faces of the buttress, and of the side faces of the buttress with the front face. Evidently the point I is one point in the line of intersection of the main wall and the side face of the buttress. The highest point common to the main wall and the side face of the buttress is c''. This is shown in plan in a line cd parallel to AB or EF, and at a distance from EF equal to the perpendicular distance of c'' from $E''E'''$ in section. The point is also shown in plan in a line ce parallel to IG, and at a perpendicular distance from it equal to $\frac{1}{6}$ of 16 ft. 4 in. (the height of c'' above $A''E'''$), the slope of the side face being 2 in. to 1 ft. The intersection of the two lines cd and ce in the point c gives the other end of the line of intersection of the face of the main wall and the side face of the buttress. Likewise the highest point common to the front and side faces of the buttress is represented by a'' in the section. This point in plan will be found in a line ab parallel to GH and at a distance from it equal to $\frac{1}{4}$ the distance of a'' above $G''E'''$, the front face of the buttress having a batter of 3 in. to 1 ft.; it will also be found in a line af parallel to IG, and at a distance from it equal to $\frac{1}{6}$ the distance of a'' above $G''E'''$. The intersection of

the lines *ab* and *af* gives the point *a*, the horizontal projection of the top point of intersection of the front and side face of the buttress. Draw the lines *c*I, *ca*, and *a*G. The horizontal projection may now be completed, the other side of the buttress being symmetrical with respect to the axis UV.

The vertical projection of the buttress is made by projecting points of the plan up to lines representing the traces of the planes in which they lie, and by joining the successive points.

Remark.—It will be better in practice to have the sets of lines *cd* and *ce*, and *ab* and *af*, the intersections of which give the directions of the lines of intersection of the faces, as far from the foot of the wall as possible, especially if distances are to be taken by scale from the drawing. In the plate this was not done on account of increasing the number of construction lines.

It will be better, before giving the directing instruments, to divide the structure into courses and stones according to the specifications for ashlar masonry given in Chapter I, Art. 7. The structure is divided into horizontal courses as shown in the plate. The arrangement of headers and stretchers should conform to the specifications. Joints must be allowed for, and particular attention paid that the stones of the several courses break joint..

57. The Directing Instruments.—For a structure as simple as this one the general drawings with dimensions and a complete set of specifications would be all that are necessary to be sent to the quarry, as the foreman himself could readily make all the patterns needed for cutting the stones. However, in case it is essential that the courses have a certain thickness and that the stones be arranged in a certain order, a detailed drawing of each course and stone must be made.

The following bevels will be of assistance in cutting the stone. T_1 is the bevel containing the diedral angle between the base and front of any buttress stone, T_2 (not shown) containing the diedral angle between the base and either side face of the buttress.

Patterns of the several faces of the stones may be used as checks upon the bevels. The pattern of the top face of the buttress may be found by revolving it about $c'd'$, until it becomes parallel to **V**. Those of the side and front faces of any stone by revolving them about lines representing the horizontal projections of their bases,

until they become parallel to **H**. This latter construction is not shown in the plate.

In detailing successive courses particular care must be taken at the angles I, G, H, and J. The stones of the buttress must be well bonded with the stones of the main wall. The sketches in the plate show an arrangement of two consecutive courses. The main points to be noted are that there should be no stones with re-entrant angles at the points I and J. That joints of a stone situated in two faces, as at the angles H and G, are perpendicular to the faces. Note the arrangement of the stones in the two courses at the points I and J. The upper stone of the buttress should extend at least 6 inches into the main wall. The joints of the stones in back are left rough.

58. Stone-cutting.—Select a rough block in which the finished stone may be inscribed, and bring the intended base of the stone

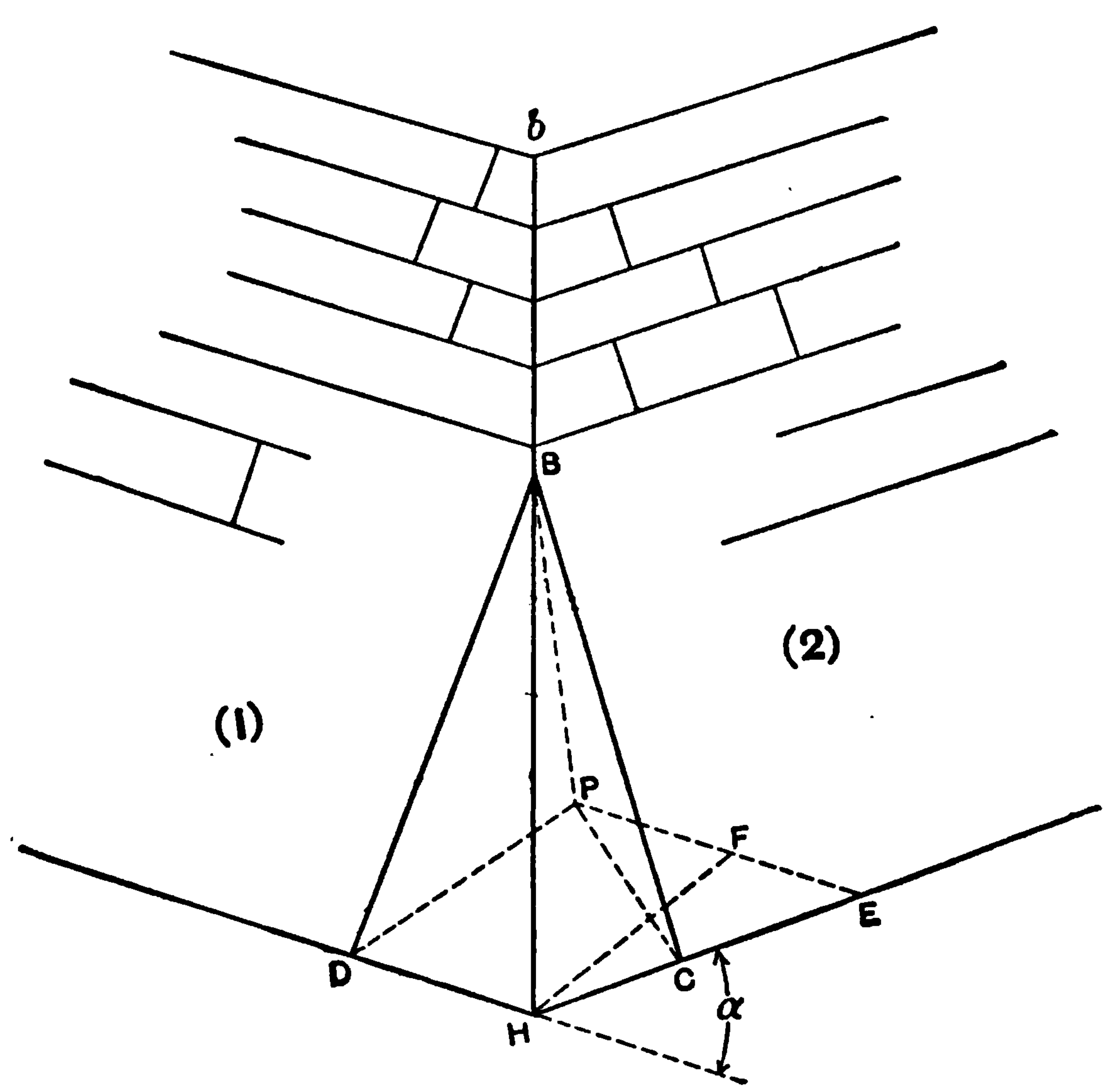


FIG. 36.

to a plane. Cut the bottom face by use of its pattern, and from it work the other faces by use of their respective bevels, on which the widths of the several faces are marked. The patterns of the faces may be used as checks on the work.

59. In a structure of this kind it is best not to scale dimen-

sions from the drawing. In order not to be obliged to do this, we must find the face angles aGH, aGI, and cIG, so that we may obtain the exact distances between the line bH and aG, and between the lines aG and cI, in order to find the lengths of the several courses in the front and side faces of the buttress. These are obtained as follows: to find the length of any joint on the face GHab, find the angle made by the lines GH and Hb in the plane GHab, or, better, find the amount of departure of the line Hb from a line drawn in the plane GHab from a point *one unit* vertically above the base and perpendicular to the line HG. In Fig. 36 let the planes (1) and (2) have batters S_1 and S_2, and let the angle made by their traces on the base plane be α.

From a point B in their intersection one unit vertically above the base plane, draw BP perpendicular to the base plane, BD perpendicular to the trace DH, and BC perpendicular to the trace HE.

Connect D and P, and C and P. Draw PE parallel to DH and HF parallel to DP. If the lengths of HD and HC can be found, they will be the desired departures above mentioned. From the figure we obtain the following equations:

$$S_3 = \mathrm{HD} = \mathrm{PE} - \mathrm{FE} = \frac{\mathrm{PC}}{\sin\alpha} - \frac{\mathrm{HF}}{\tan\alpha} = \frac{S_2}{\sin\alpha} - \frac{S_1}{\tan\alpha}$$

and

$$S_4 = \mathrm{HC} = \mathrm{HE} - \mathrm{CE} = \frac{\mathrm{HF}}{\sin\alpha} - \frac{\mathrm{PC}}{\tan\alpha} = \frac{S_1}{\sin\alpha} - \frac{S_2}{\tan\alpha}.$$

For any other height the figures would all be similar to those given in the figure, and the quantities need only be multiplied by the given height.

Example.—In the buttress $S_1 = \frac{1}{4}$, $S_2 = \frac{1}{6}$, and $\alpha = 69°\ 27'$.

$$S_3 = \frac{\frac{1}{6}}{\sin 69°\ 27'} - \frac{\frac{1}{4}}{\tan 69°\ 27'} = .085,$$

and

$$S_4 = \frac{\frac{1}{4}}{\sin 69°\ 27'} - \frac{\frac{1}{6}}{\tan 69°\ 27'} = .200.$$

Now in the plane GHab a longitudinal joint at 10 feet above the base will be shorter than the line GH by 2 (.085 × 10) or 1.7 feet. The joint is then 3 ft. $3\frac{5}{8}$ in.

The length of the corresponding joint in the face HJ*bd* would be found by taking $10 \times .2$ from HJ, and adding at the other end an amount which can be figured from the batters of the two intersecting planes HJ*bd* and JBD*d* similarly to the case shown.

60. Exercises.—1. Draw an isometric view of the top stone of the buttress, with all the necessary patterns for cutting the stone.

2. Make a paper model of the same stone.

3. Cut the same stone from plaster.

4. Let the main wall and buttress each have a coping extending beyond their front faces, and at least 6 inches into the main wall. Make the necessary drawings for the structure.

5. Take the measurements and make a complete drawing of a Gothic buttress on some church or building.

Art. 3. The Recessed Flat Arch or Plate-band.

Plate I.

61. An arch whose arched surface is plane is called a flat arch or plate-band. This form of construction should not be used for spans exceeding 10 ft.

62. Projections.—A rectangular gateway DC*cd* — A′B′C′D′ extends through a wall. The door folds against the vertical surface B′R′C′M′D′L′A′Q′ in the plane *ml* in plan. D′C′ is divided into five equal parts and the joints radiate from a point x_1 below D′C′. Fig. 3 is a vertical section through the keystone. A top view is given instead of a plan, in order to bring out the horizontal joints on the back of the arch. With this view, the front elevation, and the vertical section, the student should be able to get a clear understanding of the problem. Thus, GF in the top view corresponds to F′G′ in the front elevation; H*h* in top view represents the horizontal joint through H′ in the front elevation. There is a shoulder at F which has the same vertical projection as *f* in the front elevation, and which is represented by F*f* in the top view; E*e* is the horizontal joint through E′.

63. Directing Instruments.—Take the irregular stone D′E′F′G′, etc. The two principal patterns are for the radiating joints E′H′ and D′K′. The pattern for the radial joint represented by E′H′ can be found by revolving it about itself (not shown), until it comes into the plane HN. Fig. 4 is the pattern for this joint sur-

face, in which $H'G' = H'G'$, Fig. 2; $H'F'' = H'F'$; $H'E'' = H'E'$; $H'h' = Hh$; $F''F' = Nn$; $F'f' = Ff$; and $E'e' = Ee$. The pattern for the joint D′K′ and other joints may be found in a similar manner. Patterns of other faces will be given in the next paragraph.

64. Stone-cutting.—Take the stone D′E′F′, etc., for example. Select a block of stone in which D′E′F′, etc., can be inscribed, the thickness of which is equal to Hh. The face of this block is shown in the front elevation, part of which is in dotted lines. There is no fixed order in cutting, but the following is a good one. Suppose we start with the joint E′H′, as being the largest and most important. Work the surface of the stone to a plane and mark the edges by use of the pattern Fig. 4. The back and front faces are wrought square by use of the square, and the faces are completed by their patterns, D′E′F′G′H′I′J′K′ and G′H′I′J′K′. The top and bottom faces are either wrought square with the back, or they can be wrought from the joint face E′H′ by use of the two bevels T_1 and T_2 shown in the front elevation. I′J′ is square with the back, and the joint face D′K′ is found by a pattern constructed similarly to Fig. 4 for the joint E′H′.

As an aid in seeing clearly the shape of some of the stones let us draw an isometric view of the stone $X'W'V'C'z'$ to an enlarged scale. On the coordinate axes, Fig. 5, lay off $O'X'$, equal to the width of the stone $z'X'$, and draw the front face of the stone, the edges of which are shown in their true size in elevation. $O'z'$ is taken equal to the width of the stone $= Xx$, Fig. 2. In Fig. 5, lay off $S'n = Nn$, Fig. 2, and $nY' = nM$, and draw $S'Y'$; $Y'y' = Mm$; $y'Z' = B'R'$. Drawing verticals through Y', y', Z', and z', and taking the measurements from the elevation, the drawing is easily completed.

65. Variations.—The above case is the common one that occurs. Among the more complicated cases may be noted, 1st, the skew plate-band in a vertical wall; 2d, the right plate-band in a cylindrical wall; 3d, the skew plate-band in a cylindrical wall; 4th, the skew plate-band in a conical wall. For these more complicated cases the student is referred to "Cours Pratique de Coupe des Pierres," by H. Echenoz, Paris, 1881.

66. Exercises.—1. Make an isometric drawing of the keystone. 2. Make an isometric drawing of the stone D′E′H′I′J′K′.

Art. 4. Bridge Pier with Plane Faces.

Plate II.—Pier 3 of the Middletown and Portland Bridge.*

67. Pier 3 of the Middletown and Portland Bridge is a good example of a pier with plane faces. The upper end or nose of the pier is pointed, the batter of the side planes forming it is 3 in. to 1 ft. It is shaped in this manner to turn aside driftwood, ice, etc., which might otherwise damage the pier. As will be seen from the drawing, the draw span is on one side of the pier, while the fixed span rests on the other side. The pier was constructed of Portland brown sandstone. Rubble masonry, composed of large stones, and laid so as to be well bonded together, and bedded in cement mortar was used in filling the center of the pier. The foundation is of piles and timber.

68. **Specifications.**—The specifications according to which a pier like this would be built are those given for First-class Masonry in Chapter I, Art. 7.

The dimensions on a general drawing for a structure of this class should be as complete as possible in order that no dimensions need be scaled from the blue print, and that the work may be carried out in exact accordance with the specifications. In this case the plan of each course was not made by the engineering force, but was laid out at the convenience of the contractor, subject, of course, to the specifications as regards location of headers and bond. The plate gives an ideal elevation and section of the pier with respect to headers and stretchers, the centers of the headers being placed exactly over the centers of the stretchers. To save stone the dimensions of the stones may be changed slightly, so long as the distances between governing points remain the same. The detail plans of the courses would be made similarly to those in the Glasgow bridge, given in Plate XIII. The dimensions of the pier under the coping and the batters of the side and end planes determine the dimensions of the several courses. Having given the batter of the side planes forming the nose, it is necessary to find the batter of the line of intersection of the two faces. This is found in a similar manner to that in the buttress (§ 59). The following are extracts from the specifications:

* Proceedings of Connecticut Civil Engineers and Surveyors Association for 1896.

"The stones are to be cut to lay $\frac{3}{8}''$ joints, 18″ back from the face on the beds, and 12″ back on the vertical joints. No stretcher shall have less bed than rise, the average being $1\frac{1}{2}$ times the rise. No course shall be laid over 8 feet along the face of the work without a header. The headers cannot be less than 6 ft. in length, and must occupy 25 per cent. of the area of the face. Where the thickness of the piers will not admit of 6-foot headers shorter headers are allowed, with a certain proportion of through headers. The specifications for the rubble masonry, which is used in filling the centers of the piers and in backing up the abutment, require large, sound stone, laid so as to be well bonded together, and bedded in cement mortar.

"All the ice-breakers, copings, and tops of parapet walls and steps on the wing walls are to be rough-pointed. All the bridge seats and bearings for iron-work are to be bush-hammered, and all corners and angles to have a 2″ chisel draft-line, cut to the true batter of the pier."

69. Exercises.—1. Divide the pier into courses, making allowance for joints.

2. Make a plan of two consecutive courses of this pier showing the arrangements of the different stones, conforming to the specifications.

3. Calculate the contents of the pier.

4. If a pier of this class is in your neighborhood, take the necessary measurements and make the general drawings.

ART. 5. BRIDGE ABUTMENT.

PLATE III.

70. A common form of wing abutment * is taken to represent this class of structure. The example given is a typical design. A plan, an elevation and a section through the center are given. The abutment was designed with the following data:

Top of footing to be 14 ft. 9 in. below bottom of coping. Thickness of wall under coping = 6 ft. Batter of front face of abutment and front face of wing walls to be 1 in. to 1 ft. (except top stones of the wing). The back faces of the wing walls and abutment are vertical. Each wing makes an angle of 30° with

* Essentially that given by Baker

the head wall. The wing walls are stepped to conform to the slope of the earthwork, which is $1\frac{1}{2}:1$.

The top of tie or base of rail is 8 inches above the top of the parapet wall. The width of road-bed at bottom of ballast is 16 ft., and the depth of ballast is 14 inches. Height of parapet wall is 4 ft., the width of which at top is 14 ft. 6 in., and at bottom is 23 ft. 6 in., there being three steps with 1 ft. rise and 18 in. tread. Thickness of coping is 18 in. The width of the head at the top of the footing is 22 ft. 8 in. The abutment has two foundation courses, as shown, built of concrete. The dimensions of the pedestals upon which the bridge rests are given on the plate.

The length of the coping and wing walls are determined by the slope of the earthwork. The steps of the wings are capped by stones, each of which extends 3 in. beyond the front face of the wall, and 3 in. under the stone above it. The lowest step extends only to the toe of the wing wall. The width of the wing wall at its end is 3 ft. 6 in. The step stones are cut square on the back.

71. *Specifications.*—The specifications according to which a structure of this class is built are practically the same as those given for "First-class Railroad Masonry" in Chapter I, Art. 7. No special detail drawings are necessary, if care is taken in making out the specifications.

The abutment is cut up into courses and stones in order to show the student how the headers and stretchers are arranged. The thickness of the courses is shown in the section, no allowance being made for joints which are specified as $\frac{1}{2}$ in. Note that the slope of the earthwork conforms to *front* face of the steps.

Half-views are used on this plate only to economize space, but in practice this method is not generally used.

72. Common variations from this example in the form of wing abutments, with respect to the sections of the wings and head, are:

1st. The back faces instead of being vertical may have an even batter.

2d. The front faces may have an even batter, while the same effect is produced on the back by use of steps.

3d. The front faces of the steps are sometimes set parallel to the line *bc*, in which case the batter is given at right angles to this line.

The parapet wall in these three cases, as also in the example

given, is sometimes battered on the back face. The bridge often rests directly on the coping, there being no pedestal blocks.

For examples of the T and U abutments, the student should consult "Baker's Masonry Construction."

73. **Exercises.**—1. Make an isometric drawing of the pedestal block.

2. An isometric of one of the step stones.

3. Show a section of the wing wall near its junction with the main wall.

4. Check the length of the wing wall.

5. Calculate the amount of masonry in the structure.

6. Design an abutment with any of the variations noted above.

7. Take the measurements of a wing abutment in your neighborhood, and make the drawings of it.

ART. 6. ARCHITECTURAL STONEWORK.

PLATES IV–VI.—THE WORCESTER CITY HALL.

74. The drawings on these plates are examples of carefully detailed work. All the face-stones in this building are dimension stones. The stone for the building was Milford granite.

Plate IV is a key drawing to the building, showing the interesting method of marking the stones for identification. The plan is divided into eight portions—A, B, C, etc., as shown, and the elevation is divided into five portions, A, B, C, etc. Thus stones in portion "G" of the plan and in the section "A" of the elevation between the top of the basement floor and the first floor are marked G. A. 1, G. A. 2, etc., the numbers referring to the several stones as shown on the detailed elevation of that portion of the building. Stones in other portions of the building are designated similarly. By this system of marking, stones for a certain portion of the building may be deposited near their final resting-place, with but little rehandling.

Plate V is a part of portion G. A. As noted on the drawing no allowance has been made in the figures given for beds or joints, but that one quarter inch should be allowed for all joints.

75. **Entrance Porch.***—Plate VI is a good example of a com-

* This plate may well be studied with the next chapter.

plex piece of architectural masonry. The plan of the steps is given, the elevation of the abutting wall, and developed elevations on two sides of each wall. These are the drawings which were furnished the stone-cutters for this work.

The face of each stone of the curved walls is obtained by bending flexible patterns obtained from the developments to the proper curves as shown in the plan. These patterns are commonly made of zinc. Note that each step pitches one quarter of an inch so that the steps will drain.

76. In *general* the method of procedure in designing a building of this nature is about as follows: The architect makes $\frac{1}{8}$- or $\frac{1}{4}$-inch scale elevations, which are furnished the contractor, and in addition to which three-quarter and full-size details and plans are furnished. From these the contractor prepares the cutting or setting plan of the stonework, giving the dimensions of each stone. These, when checked and approved by the architect, are used by the contractor in the quarries and on the work.

Plates V–VII are the plans prepared by the contractor. The superintendent at the quarries has the necessary patterns made. The stones are carefully inspected and marked at the quarries before being shipped.

Sometimes the complete cutting plans are furnished the contractor by the architect, and occasionally the engineer or architect furnishes full-sized patterns of zinc or other material for every stone not rectangular. This latter method is extensively used on the United States government work.

77. **Exercises.**—1. Let the student prepare a key drawing for marking the stones of some prominent building.

2. Make the contractor's plan and elevation of a portion of the building.

3. Check the calculations for the lengths of the curves on Plate VI.

Plate VII.—Church Masonry.

78. This is a good example of broken range work, sometimes called broken ashlar. The illustration is the west elevation of the transept. The stone for this church was buff Bedford limestone and granite, the trimmings being of limestone. The key drawing is not shown, but was similar to the one given in Plate IV. Each

stone of the entire church is a dimension stone. At the corners are Gothic buttresses, an elevation of one of which is given. The combination of the two kinds of stone gave a very beautiful effect.

After carefully studying these drawings, the student should be able to arrange and dimension the stone in a similar building.

CHAPTER IV.

STRUCTURES CONTAINING DEVELOPABLE SURFACES.

ART. 1. ARCHES. DEFINITIONS.

79. Fig. 37 clearly illustrates the parts of an arch, to which may be added the following definitions:

Voussoir or *Arch stones:* one of the stones composing the arch.

Quoins or *Ring-stones:* the voussoirs in the face of an arch.

Keystone: the center or highest voussoir.

Soffit: the inner or concave surface of the arch.

FIG. 37.—PERSPECTIVE OF AN ARCH.

Back: the external or convex surface of the arch.

Intrados: the intersection of the soffit with the face of the arch.*

Extrados: the intersection of the back of the arch with the face.*

Crown: the highest part of the arch.

Skewback: the top of the abutment if inclined.

* Often used to designate the inner and outer *surfaces* of the arch.

Springing-plane: the top of the abutment when level.

Abutment: the supporting walls of an arch.

Spandrel: a wall or walls, built on the top of an arch, usually one at each end in the plane of the face.

Spandrel Filling: the material which may be masonry or earth deposited between the spandrel walls.

Springing Line: the line of the soffit at the top of the abutment, as AI in Fig. 37.

Span: the perpendicular distance between the springing lines, as AB.

Rise: the vertical distance between the highest part of the intrados and the plane of the springing lines, as CD.

String-course: a course of voussoirs running from one end of the arch to the other.

Ring-course: a course parallel to the face of the arch.

Longitudinal or *Coursing Joint*: a joint between two adjoining string-courses.

Transverse or *Heading Joint*: a joint between adjoining ring-courses.

Arch Sheeting: all the masonry of the arch proper except the face voussoirs.

Backing: masonry, usually with joints horizontal or nearly so, carried above the skew backs and outside of the extrados.

Centering: the temporary structure erected to support the arch sheeting during construction. Fig. 42.

80. Kinds of Arches.—Arches divided according to the forms of their *soffits* are:

Plane or *Flat Arches* as illustrated in Chapter III, Art. 3.

Cylindrical Arch, one in which the soffit is a portion of a cylinder.

Conical Arch, one in which the soffit is a conical surface.

Warped Arch, one in which the soffit is a warped surface.

Arches divided according to the form of the *intrados* are:

Semicircular or *Full-centered Arch*, one whose intrados is a semicircle.

Elliptical Arch, one whose intrados is part of an ellipse.

Parabolic Arch, one whose intrados is a parabola.

Basket-handle Arch, one whose intrados resembles a semi-ellipse but is composed of arcs of circles tangent to each other.

Gothic or *Pointed Arch,* one whose intrados consists of two arcs of equal circles, intersecting over the middle of the span.

Tudor Arch, one whose intrados consists of four arcs, the two intersecting at the crown not being tangent to each other.

81. Arches divided according to the *direction* of the *axis* with respect to their other parts are:

The Right Arch, one in which the axis is horizontal and the planes of its faces are at right angles to the axis. The planes of the faces are termed *heads.*

The Oblique or *Skew Arch,* one in which the heads are oblique to the axis. (See Chapter V, Art. 1.)

Rampant Arch, one in which one springing line is higher than the other. The *descending* arch is also sometimes called rampant. To distinguish the two, when *one end* of the *axis* is higher than the other it may be called *longitudinally rampant,* and when one *springing line* is higher than the other it may be called *transversely rampant.*

Other forms of arches are:

Groined and Cloistered Arches, those formed by the intersection of two or more cylindrical arches. (See Arts. 6 and 7.)

Annular Arch, an arch generated by the right section of an arch revolving about a line lying in the plane of the section, but not intersecting it. This line is usually vertical and also perpendicular to the span of the arch.

If the right section of an arch revolves around a vertical through the keystone, a *dome* is produced; if it moves in a straight line on the springer, a *vault* is produced.

ART. 2. GEOMETRICAL CONSTRUCTIONS.

PLATE VIII.

82. **Arcs of Circles.**—The compasses are used for drawing circular curves up to about 15 in. radius. The beam-compass is used for drawing circular curves from 15 in. up to 4 or 5 ft. radius. When the radius exceeds about 5 ft. it is generally necessary to describe the arc without making use of the center. Knowing the length of the chord of the arc and its middle ordinate or rise, we proceed as follows: In Fig. 17 let AB be the given chord and CD the given rise of the required arc. Draw AD and draw AE

perpendicular to it, to meet the tangent of the curve drawn through the point D, in E. Also draw AF perpendicular to AB. Divide CA, AF, and DE into the same number of equal parts and number the corresponding points of division as in the figure. Then the lines joining like points on CA and DE will meet those radiating from D to the points on AF, in points of the desired arc.

Note.—The correctness of the above construction may be seen by prolonging the lines 11, 22, etc., until they intersect in the point G (not shown). Then it might be proved that DG is the diameter of the circle of which the arc AD is a portion.

83. It is often convenient to plot the points in a circular arc by calculation, which may be done as follows (Fig. 18):

Let R = the radius of the arc, C = the half chord, x = the distance from O to any point on the chord, y = the ordinate from the chord to the arc, and O′ the center of the circle.

$$\text{Then EF} = \sqrt{(\text{O}'\text{E})^2 - (\text{O}'\text{F})^2} = \sqrt{\text{R}^2 - x^2};$$

$$\text{PF} = \text{OO}' = \sqrt{(\text{O}'\text{B})^2 - (\text{OB})^2} = \sqrt{\text{R}^2 - \text{C}^2};$$

$$\text{EP} = y = \text{EF} - \text{PF} = \sqrt{\text{R}^2 - x^2} - \sqrt{\text{R}^2 - \text{C}^2}.$$

84. *To find the radius of a segmental arch, given its rise and span.* In Fig. 19 let ADB be the arch of which the radius is required; AC the half span, denoted by s; and CD the rise, denoted by h. Let O be the center of the arc ADB, and let the radius AO be denoted by R. Draw AD, and at its middle point, E, erect a perpendicular meeting DC produced in O.

Then the right triangles ACD and OED are similar, and CD : DE :: AD : DO, or $\text{DO} = \text{R} = \dfrac{\text{DE} \times \text{AD}}{\text{CO}} = \dfrac{\text{AD}^2}{2\text{CO}}$, since $\text{DE} = \frac{1}{2}\text{AD}$.

$$\text{But AD} = \sqrt{\text{DC}^2 + \text{AC}^2} = \sqrt{h^2 + s^2}. \quad \therefore \text{R} = \frac{h^2 + s^2}{2h}.$$

85. Examples.—1. The Cabin John Arch* is a segmental arch, whose span is 220 ft., and whose rise is 57.26 ft.; what is the radius of the arc? *Ans.* = 134.29′.

2. The Bellows Falls Arch, on the Fitchburg R. R.,† is composed of two equal segmental arches, the spans of which are 140 ft., and whose rise is 20 ft.; what are the radii of the arcs? *Ans.* = 132.5′.

* *Eng. Record*, July 29, 1899, vol xl p. 191.

† *Eng. News*, June 21, 1900, vol. xliii. p. 402.

86. *To find the length of a circular arc.* Suppose we know the chord and middle ordinate. If the radius is not known, it may be found as in § 84. In Fig. 19 the semicircumference of a circle with a radius AO = R is equal to 3.1416 times R. The $\frac{1}{180}$ part, or that corresponding to a single degree, is therefore equal to R × 3.1416 ÷ 180, or R × .017453. We now have simply to find the angle at the center of the circle subtended by the given chord. In the figure $\sin \frac{1}{2} \angle AOB = \frac{AC}{AO} = \frac{s}{R}$. From a table of natural functions find the angle and let n be the number of degrees in the *whole* angle. Then the length of the arc ADB = $n \times R \times .017453$.

This problem is very useful in finding the length of the intrados of an arch of known span and rise, for the purpose of dividing it into voussoirs or for laying down the development of the soffit.

From the data given in the preceding paragraph solve the following examples.

87. Examples.—Find the angle at the center and also the length of the arc of the Cabin John Arch.

Ans. Angle = 109° 59′ 40″, practically 110°, arc = 237.833 ft.

2. Find the angle at the center and the length of the arc of the Bellows Falls Arch.

Ans. Angle = 63° 46′ 53.6″, arc = 147.44 ft.

3. After having the lengths of the intradoses of the above arches divide them into courses and find the width of a course. Compare these with the number of courses in the arches as actually built.

88. Ellipses.—*To construct an ellipse having given its axes.*

1st Method. (Fig. 20.) Let AB and CD be the given axes. With C or D as a center and with a radius equal to AO, the semi-major axis, describe two arcs intersecting AB at F and F′, which are the foci of the ellipse. Then with F and F′ as centers, and a radius equal to any part of the major axis AB, describe four arcs, E, E, E, E; also with the remaining part of the axis as a radius describe four other arcs. The intersection of these four pairs of arcs will be points in the circumference of the ellipse. Repeat the operation for other divisions of the major axis.

2d Method. Having found the foci as in the previous method, place pins at the points F and F′. Take a string with a loop at

each end, the total length of which from end to end of loop is equal to the major axis. Place the loops over the pins at F and F′, and trace the curve by a pencil, the string being kept equally stretched all the time. This method is difficult of execution.

3d Method. (Fig. 20.) On the edge of a stiff piece of paper mark a distance, *ad*, equal to AO, one half of the major axis, and from the same point, *a*, a distance *ac* equal to OC, one half the minor axis. Then place this strip in different positions so that the point *c* will always fall on the major axis, and so that the point *d* will fall on the minor axis; then the point *a* will mark points on the circumference.

4th Method. An ellipse may be constructed by intersecting lines as in the construction of the circle (§ 82), having given the axes AB and CD, Fig. 21. Describe a rectangle upon the given axes, and divide the major and minor axes into the same number of equal parts, at the points 1, 2, 3, etc., and 1′, 2′, 3′, etc. Then draw the lines C1′, C2′, C3′, etc., and D1, D2, D3, etc., the intersections of which will be points on the curve. Trace the curve through these points.

5th Method. The ordinate from a point on the major axis to the curve may be computed from the equation of the ellipse as follows: Let $a = \frac{1}{2}$ the major axis, $b = \frac{1}{2}$ the minor axis, $x =$ the distance from the center to the foot of the ordinate, and $y =$ the ordinate. Then $y = b/a \sqrt{a^2 - x^2}$.

89. *To draw a tangent to an ellipse at any point on the ellipse.* Fig. 20. Let p be the point on the ellipse at which we wish to draw a tangent. Draw pF and pF′ to the foci. Bisect the angle FpF′ by the line px and draw pt perpendicular to px. Then pt will be the tangent to the ellipse at the point p.

90. *To draw a tangent to an ellipse from a given point without the ellipse.* Fig. 21. From the given point P as a center, and a radius equal to PF′, its distance to the nearest focus F′, describe an arc. From the other focus, F, with a radius equal to the major axis AB describe another arc cutting the first one at G and H. Draw GF and HF′ cutting the ellipse at I and J. Then the lines PI and PJ are tangents to the ellipse.

91. *To draw a joint in an elliptic arch through any point p.* In Fig. 20 bisect the angle FpF′ as before by the line px, and produce this line backward, and we obtain the required joint.

92. The Parabola.—A parabola is a curve any point of which is equidistant from a fixed point, as F in Fig. 22, and a given line AB. The fixed point is called the *focus*, and the given line is called the *directrix*. It may also be considered an ellipse whose major axis is infinite.

93. *To construct a parabola when the focus and directrix are given.* In Fig. 22, from F as a center, describe any arc having a radius greater than EF; lay off the radius from A, as AH, and at H erect a perpendicular. The intersection of this line with the arc will be a point on the parabola.

94. *To construct a parabola having given the base CD and height AB.* In Fig. 23 let CD be the base and AB the height. Construct the rectangle CDEF. Divide each half of the base into any number of equal parts, and number them as shown. Divide DE and CF into the same number of equal parts, and number them from the top down. From the points on CD draw vertical lines, and from the points on DE and CF draw lines to A. The intersections of the lines 1, 1; 2, 2; etc., will give points of the parabola.

95. *Tangent.*—In Fig. 22 a tangent to any point on the parabola may be drawn by bisecting the angle between the line from the point to the focus, and a line from the point to the directrix, or by making ET = EH, and drawing the line TP.

96. *Ordinates.*—The length of the ordinate HP to any point, P, may be calculated from the equation of the parabola referred to the axis EH and EL. The parameter being the double ordinate through the focus $= QQ' = 2AF$, $x = EH$, and $y = HP$, then $y^2 = 2px$.

If the parabola is given by the lengths of PP′ and EH, as in the case of a parabolic arch with known span and rise, the same equation may be used, p being found from the two known coordinates EH and HP.

ART. 3. OVALS.

PLATE VIII.

97. The semicircular or full-centered arch is often replaced by a segmental arch on account of limited space for the rise. An elliptic arch is generally more graceful than a segmental arch having the same rise and span.

The convenience of circular over other curved work has led to the substitution of compound curves composed of arcs of different radii, to take the place of the true arc of an ellipse. They should not be used when in combination, as in groined and cloistered arches.

When the tangents to the curve at the springing line and crown are perpendicular respectively to the span and rise, the curves will belong to the basket-handle class of curves, commonly called *ovals*. Curves fulfilling these conditions will have an odd number of centers.

When the tangents to the curves at the springing lines are perpendicular to the span, while those at the crown are oblique to the rise, the curves will belong to the class of pointed or obtuse curves. Curves fulfilling these conditions will have an even number of centers.

The most common kinds of pointed arches are the Gothic arch and the Tudor arch. The former has two centers, and the latter has four centers. They are used principally in architectural work. The most common kinds of ovals are the three-centered and the five-centered.

98. Three-centered Ovals.—*The General Construction of a Three-centered Oval.*—Fig. 24. It is evident in this case, that having the rise and span of an arch, and the directions of the tangents at the springing lines and crown, an infinite number of curves may be constructed fulfilling the condition that the curves be tangent to each other. The general construction will first be given and then certain conditions will be imposed, making the problem more definite.

Let AB be the span and OC the rise. On the span and rise set off any distance AD = CE and less than the rise OC. Join D and E, and bisect the line DE by a perpendicular which meets CO

produced at G. Then D, G, and a point on OB at a distance from B equal to AD, will be the centers of the required oval.

Let R denote the radius GC at the crown, and r the radius DA at the springing line. Denote the half span AO by s, and the rise OC by h. Then in the right triangle OGD, $(DG)^2 = (OG)^2 + (DO)^2$,

or
$$(R - r)^2 = (R - h)^2 + (s - r)^2,$$

whence
$$R = \frac{s^2 + h^2 - 2sr}{2(h - r)},$$

or
$$r = \frac{s^2 + h^2 - 2hR}{2(s - r)}.$$

This equation may be satisfied by an infinite number of values of R and r. To make the problem more determinate we may impose the following conditions:

99. 1st. *To construct a three-centered oval when each of the arcs shall be 60°.* In Fig. 25 let AB be the span and OC the rise. With O as a center and a radius equal to OB describe the circular arc BDE of 90°, and lay off the angle DOB = 60°, and draw the lines DE, DO, and DB. From C draw CF parallel to ED, cutting DB in F, and from F draw FH parallel to DO, cutting OB in J, and CO produced in H. From J as a center and radius equal to JB describe the arc BF, and from H as a center with a radius HF describe the arc FC. A similar construction on the other side of OC will give the required curve BFCIA.

The proof that the above construction gives a three-centered oval, the arcs of which are 60°, is evident, since the radii FJ and HF of the two arcs coincide in direction, and the arcs are therefore tangent to each other at the point F. The angle FJB = DOB = 60°.

In application to arches, when the rise is greater than one-third the span, the three-centered oval with 60° arcs affords greater capacity for the flow of water than does a semiellipse with the same span and rise, since the radius of the former at the point B is greater.

100. 2d. *To construct a three-centered oval with the condition that the ratio of the radii of the arcs be a minimum.* From the general equation for a three-centered oval (§ 98),

$$R = \frac{s^2 + h^2 - 2sr}{2(h - r)}.$$

Differentiating this fraction and placing the first derivative equal to zero,

$$\frac{d\left(\frac{R}{r}\right)}{dr} = 0.$$

After the terms have been reduced, and solving for r, we get

$$r = \frac{\sqrt{s^2+h^2}}{s}\left(\frac{\sqrt{s^2+h^2}-(s-h)}{2}\right);$$

and substituting this value of r in the other equation in § 98 and reducing, we get

$$R = \frac{\sqrt{s^2+h^2}}{h}\left(\frac{\sqrt{s^2+h^2}+(s-h)}{2}\right).$$

The construction is as follows, shown in Fig. 26: AB $= 2s$ is the span, and OC $= h$ is the rise of the desired curve. Draw AC and set off CD $= s - h$. Bisect the distance AD by a perpendicular and produce it to intersect AO in G, and OC prolonged in H. From the points G and H as centers, and radii equal to GA and HI, describe the arcs AI and IC, and the curve AIC will be the half of the one desired.

In the similar triangles AEG, AOC, and EHC,

$$r = \text{AG} = \frac{\text{AC}}{\text{AO}} \times \text{AE} = \frac{\sqrt{s^2+h^2}}{s}\left[\frac{\sqrt{s^2+h^2}-(s-h)}{2}\right],$$

and

$$R = \text{HC} = \frac{\text{AC}}{\text{OC}} \times \text{EC} = \frac{\sqrt{s^2+h^2}}{h}\left[\frac{\sqrt{s^2+h^2}-(s-h)}{2}\right].$$

These equations agree with those deduced above.

101. *Length of Arcs.*—It is necessary in a three-centered arch to know the lengths of the respective arcs in order to find the width of the voussoirs. These are obtained as follows: In Fig. 24 suppose we have the span AB given, the rise OC. and also the two radii AD $= r$ and GH $=$ R. Then we can find the angle HGC, which is one half the central angle of the arc HI, since $\sin \angle \text{HGC} = \frac{\text{DO}}{\text{DG}} = \frac{s-r}{R-r}$. Then the central angle ADH of the arc AH $=$ angle ODG $=$ (90° $-$ angle HGC). Then knowing the

value of the central angles and the radii of the two arcs, the lengths of the two arcs may be found (§ 86).

Ovals of five centers are preferable to three-centered ones when the rise is less than one third the span.

102. Five-centered Oval.—*To construct a five-centered oval which shall conform as nearly as possible to a semiellipse on the same axes.* (Fig. 27.) This is the most common case of the five-centered oval, and will be the only one given. In an ellipse the radius of curvature at the extremity of the minor axis is a third proportional to the semiminor and semimajor axes, and the radius of curvature at the extremity of the major axis is a third proportional to the semimajor and semiminor axes. Let $CO = h$, $AO = s$, and $CO = \frac{1}{2}AO$. Let $R =$ the radius at extremity of the semiminor axis, and $r =$ the radius at the extremity of the major axis. Then from the above $h:s::s:R$, or $R = \frac{s^2}{h} = 2s$, and $s:h::h:r$, or $r = \frac{h^2}{s} = \frac{1}{2}h$. In an ellipse the radius of curvature is constantly changing, and a radius may be found which shall be a mean proportional between these radii already found, and it will also be a mean proportional between the semiaxes, since from the above equations $R = 2s$, and $r = \frac{1}{2}h$. Hence $R \times r = 2s \times \frac{1}{2}h = sh$. Calling the intermediate radius r_1, we have $r_1 = R \,.\, r = sh$.

The construction is as follows: On AO lay off $AK = r = \frac{1}{2}h$. Make $OB = OC = h$, and on AB as a diameter describe a semicircle BFA. Prolong OC to meet the semicircle at F. Produce CO to H, making $HC = 2s = R$, and on it lay off $OG = FC$, and with H as a center and radius HG describe an arc GD. Lay off $AJ = OF$, then with K as a center and radius KJ describe the arc JD cutting the arc GD in D. The points H, D, and K are the centers of the three arcs with radii respectively equal to HC, DL (= OF), and AK. The other half of the oval is constructed similarly. The proof of this construction is as follows:

$OF = \sqrt{AO \times OB} = \sqrt{sh}$. The radius AK by construction $= \frac{1}{2}h = r$, and $AJ = OF = DL = \sqrt{sh} = r_1$, and $HC = 2s = R$.

$\therefore r_1^2 = R \,.\, r = sh$ which agrees with the equation previously deduced.

103. Example.—An excellent example of a five-center stone arch is one built at Pelham, N. Y. (formerly Pelhamville), on the N. Y., N. H. & H. R. R. An illustration of this arch is given in Fig. 42 and Art. 11, with a brief description taken from the *Eng. News* of Jan. 17, 1895, vol. XXXIII. p. 34.

104. *Length of Arcs in a Five-centered Oval.*—As in the case of the three-centered oval, it is necessary to find the lengths of the arcs of the intrados in order to find the width of the voussoirs. The general solution is as follows, *knowing the radii, span, and rise:* Referring to Fig. 27, draw HK. Then KO $=$ AO$-$AK $= s-r$, and OH $=$ HC $-$ CO $=$R$-h$. $\therefore$ tan $\angle$KHO $= \frac{\text{KO}}{\text{OH}} = \frac{s-r}{\text{R}-h}$, and the side KH of the triangle KHO $=$ OK cosec $\angle$KHO. Then in the triangle KHD we know the three sides, since we have just found the side KH, and HD $=$ R$-r_1$, and KD $= r_1-r$. Solve the triangles for the angles HKD and DHK. Then the angle DKJ $=$ AKL $=$ central angle of the arc AL $= \angle$HKO$-$HKD. Then $\angle$KDM $=$ central angle of arc LM $= \angle$DKH $+$ DHK, and $\angle$DHC $= \angle$KHO$-$KHD $= \frac{1}{2}$ the central angle of the middle arc of the oval. Then having the central angles of the arcs, the lengths of the arc may be found (§ 86).

105. Examples.—1. Take the dimensions of the Pelham arch, cited in paragraph 103 and described in Art. 11, and compute the lengths of the arcs.

2. With the given span and rise, find the radii of the arcs of a five-centered oval which shall conform as nearly as possible to a semiellipse on the same axes.

3. Find the lengths of the arcs in (2).

4. Construct a true semiellipse on the given axes to a large scale. Also, in the same figure, construct the oval with the dimensions in (1) and those found in (2).

Note.—In the construction of the arch as built, a true semiellipse was swung in, and radii selected by scale which seemed most closely to conform to the semiellipse already drawn. The greatest variation from the true line of the ellipse was about 1 inch. This method of construction is the practical one. It will be seen from the calculations in (2) that the radii of the smaller arcs are slightly different from those actually used in constructing the arch.

ART. 4. A CYLINDRICAL ARCH IN A CIRCULAR WALL.

PLATE IX.

106. Problem.—A wall of a circular room is pierced by a semicircular arch perpendicular to it. It is required to obtain all the necessary patterns, bevels, etc., of the arch.

This problem may be considered as a case of two cylinders intersecting at right angles, the axis of one being vertical and that of the other horizontal.

107. The Projections.—$B'F'C'$ is the right section of the semicylindrical arch which intersects the circular wall, a segment of which is ADD_1A_1, the center being at a point P above P′ in Fig. 28. The soffit is divided into an odd number of equal parts, and the joints radiate from the center O′. In the plan the joints of the soffit appear as though they were viewed from below. The voussoirs are completed by the horizontal and vertical joints as shown; the courses therefore diminish in thickness from the springing line upward.

108. The Directing Instruments.—Let us take some one stone, as $E'F'G'H'I' - II_1FF_1$, and show how to determine the patterns of all its faces and the bevels necessary to cut the stone.

The pattern of the top face $H'G'$ will be the figure IGG_1I_1, shown in its size in plan.

The pattern of the side face $H'I'$ will be simply a rectangle of width $H'I'$ and length II_1.

The patterns of the two faces of the stone as represented by G_1F_1 and I_1F_1 for the inner face and GF and IF for the outer face must be obtained by developing the concave and convex cylindrical faces $B_1P_1C_1$ and BPC of the arch. These developments are shown in Figs. 29 and 30. In Fig. 29 the inner curve of one half the wall is set off by points from the plan in Fig. 28. Ordinates are erected at these points, and the proper heights are obtained by projecting over from Fig. 28. The development of the outer face in Fig. 30 is made in a similar manner. Then $E_1'F_1'G_1'H_1'I_1'$ and $E'F'G'H'I'$, Figs. 29 and 30, are the patterns of the inner and outer faces shown in their true size. These patterns are made of flexible material.

To construct the pattern for the face of the soffit $E'F'$ we develop the entire intrados $B'F'C'$, or under surface of the arch.

B_1C_1 and BC are the horizontal projections of the curves of intersection of the two cylinders. The right section, $B'F'C'$, is considered as taken in the plane B_1C_1. Fig. 31 is the development of the soffit, in which the straight line B_1C_1 is the length of the right section $B'F'C'$, and the several points are projected over from the plan in Fig. 28. Then EFF_1E_1, Fig. 31, is the pattern of the intradosal face $E'F'$, which must be flexible.

To find the patterns of the radial beds on $E'I'$ and $F'G'$, etc., requires that we find the true curve of the radial joints $E'I'$, $F'G'$, etc. These joints are formed by the intersection of the planes $O'I'$, $O'G'$, etc., perpendicular to **V**, with the segment of the vertical cylinder forming the wall, and are therefore arcs of ellipses. These arcs may be shown in their true size by revolving them parallel to one of the planes of projection, or by constructing the ellipses from their given axes. These ellipses will have their semiconjugate axes each equal to the radius of the circular wall and their semitransverse axes equal to the distances from O' through the respective joints to a tangent to the circular wall at extremity of diameter PX, shown for joint $U'V'$ in the figure. We will use the former method here and take the joint $F'G'$ as an illustration.

Revolve the plane of $G'F'$ about $S'F'$ as an axis. The point S' will remain stationary, being the point where the *axis* intersects the *arc;* F' falls at F'' at a distance equal to fF, and G' at G'' at a distance equal to gG; other points being similarly found and joined give the arc. Fig. 32 is the pattern of the joint face $F'G'$, to an enlarged scale, the distances GG_1 and FF_1 being obtained from the plan in Fig. 28. The other part of the construction is obvious from the figures. The other joint face may be found in a similar manner.

T_1 is an arch square, one arm of which radiates from the center of the arch and the other arm fits the curve of the intrados. A bevel T_2, having the angle $H'G'F'$, will also be of service.

109. Stone-cutting.—Consider the stone whose right section is $E'F'G'H'I'$, Fig. 28. Take a block of stone of right section and plan sufficiently large that the rectangles in Fig. 28 may be inscribed in it. We proceed as usual to cut the stone by working the side face by use of its rectangular pattern as previously given; then the top face at right angles to this is worked by use of the square and the pattern of the face; the position of the joint face

$G'F'$ with respect to the top face is found by use of T_2, and the face worked by use of its pattern, Fig. 32. The soffit is now worked by use of the arch square T_1 and the flexible pattern EFF_1E_1 in Fig. 31. The inner and outer faces may then be worked by use of their developments in Figs. 30 and 31, bent to the curves I_1F_1 and IF, Fig. 28. The other stones are obtained similarly.

110. Variations.—Almost any kind of an arch may be constructed in a circular wall, the case above given being the simplest one. There are two general divisions, as follows: In the first the intrados and extrados are cylindrical. In the second the elements of the arch radiate from a common vertical axis, the elements in every case, however, being parallel to the springing plane. In this case the inner opening is smaller than the outer one.

For the more complicated cases the student should consult "Traité Pratique de la Coupe des Pierres" by Emile Lejeune.

111. Exercises.—1. Draw an isometric view of the keystone.

2. Replace the arch by a three-centered one and make all the necessary drawings.

ART. 5. THE HORIZONTAL FULL-CENTERED ARCH.

PLATE IX.

112. Problem.—A semicylindrical arch terminated at one end by a larger semicylindrical arch perpendicular to it and on the same springing plane, and at the other end by a plane oblique to the axis and having a given inclination to the horizontal plane containing the axis.

Let the angle of skew of the oblique plane $= 15°$, Figs. 34 and 35.

Batter of the oblique plane $= 3''$ to $1'$.

The radius, $O'B'$, of the intrados of the smaller arch $= 2'\ 6''$.

The radius, $O'A'$, of the extrados of the smaller arch $= 4'\ 0''$.

The radius, RU, of the intrados of the larger arch $= 6'\ 0''$.

113. Projections. (Figs. 34–37.)—Consider **H** the springing plane and let the vertical plane be perpendicular to the axis of the arch $O_1O - O'$.

Right Section.—Let the semicircle $B'F'C'$, Fig. 34, be the right section of the soffit of the arch. Divide this into an odd

number of equal parts, and through the points of division draw the radii O′B′, O′E′, etc., and prolong them until they intersect the semicircular extrados, A′G′D′, in the points A′, I′, G′, etc. Through these points draw horizontal and vertical lines until they intersect, as G′H′ and H′I′. K′K′ is drawn giving any desired thickness to the keystone. The lines I′H′, G′H′, etc., are the exterior bounding lines of the voussoirs in right section.

Plane Face.—AD is the trace of the oblique plane on **H**, the plane containing the axis and lowest elements of the arch. The angle which AD makes with a line through D parallel to A′D′ = *angle of skew* of the oblique plane = 15°. (See Chapter V, Art. 1, for definition of angle of skew.) The oblique plane face has a batter of 3″ to 1′ perpendicular to AD. The horizontal projection of the intersection of the oblique plane and the arch may be found in three different ways, as follows:

I. Draw any line, as AL_4, perpendicular to AD. Consider the point F′, Fig. 34, at a distance F′f′ above A′D′. The horizontal projection of this point will be found in a line parallel to AD and at a distance from it = $\frac{3}{12}$ of F′f′. The point must also be projected horizontally in a line through F′ parallel to the axis $O_1O - O'$ of the smaller arch, and is therefore the intersection of the two lines in the point F. Find other points similarly, and joining the successive points we get the curves of intersection as shown in Fig. 35. EFGHI is the horizontal projection of the plane face of the voussoir E′F′G′H′I′, Fig. 34.

II. A more rapid way than (I), is to draw the line A′L‴ at a batter of 3″ to 1′ with the vertical line A′p′, by making A′L′ = $\frac{1}{4}$L′L‴. Now project horizontally the points E′, F′, etc., upon the line A′L‴ and mark the points of intersection E‴, F‴, etc. E″E‴, F″F‴, etc., will be the horizontal distances of the points E, F, etc., from the trace AD. These distances can be laid off on AL_4 with the dividers and the horizontal projections of the points of intersection found as in (I), or by projecting the several points onto AL_2, parallel to A′D′, and revolving about A till they intersect AL_4, and then drawing lines parallel to AD as before.

III. It is convenient in projecting the points to have the batter of the face taken in vertical planes *parallel* to the *axis* $O_1O - O'$, instead of *perpendicular* to the *trace* AD of the oblique plane. Consider the point G′ in Fig. 34; the batter of the plane face

measured parallel to the axis will be greater than the batter measured perpendicular to the trace AD of the oblique plane, since the distance from A to G_3 (the point where the line through G parallel to AD cuts AA_1) is greater than AG_4. $A'p'''$ represents the batter of the face in a plane parallel to the axis, the method of constructing which is evident from the figure.

To obtain the horizontal projection of the points we project them across (Fig. 34) similarly, as in (II), but to the line $A'p'''$ instead of to $A'L'''$; then down to AL_3 and around to AA_1, instead of to AL_4, and through the several points drawing lines parallel to AD as in (I) and (II).

Either method I or II will give the same results. The distances intercepted between the lines $A'p'$ and $A'p'''$ might have been laid off directly on the several elements in the direction of the axis. This way avoids numerous construction lines, but does not preserve the method of construction.

Joining the successive points obtained by any one of the three methods, we obtain the horizontal projection of the plane face of the voussoir, as EFGHI, Fig. 35. The horizontal projection of the radial joints must meet at O.

Cylindrical Face. — The two semicircular arches intersect. Both the intrados and extrados of the smaller arch extend to the intrados of the larger. Let RS and UW be the horizontal projections of the springing line and axis respectively of the larger arch.

Pass a number of horizontal planes through the arches. These planes will cut elements from each arch, the intersections of which will be points of the curve of intersection. Thus pass a horizontal plane through E′, which will cut two elements from the intrados of the smaller arch, $E'E_1$ and $N'N_1$. The intersection of these elements with the corresponding element cut from the larger arch will give points E_1 and N_1 in the curve of intersection. The curve of intersection of the extrados of the smaller arch and intrados of the larger one is found in a similar manner.

A more rapid way to find these curves of intersection is as follows: On A′D′ produced construct a semicircle tangent to the vertical line D′Q″, the radius of which is equal to the radius of the larger arch. Project points across in lines parallel to the ground-line A′D′ till they intersect the line D′Q″ and the curve D′Q‴. Then the distances intercepted between these two are the hori-

zontal distances from the springing line RS of the larger arch to the points of intersection. Thus, $Q''Q'''$, $J''J'''$, etc., Fig. 37, $= q_1Q_1$, p_1J_1, etc., Fig. 35. Or Q_1, J_1, etc., Fig. 35, can be found by projecting Q''', J''', etc., Fig. 37, onto RS produced and revolving them around D_1 in a similar manner to that used in the plane face. Joining the successive points M_1, N_1, J_1, etc., Fig. 35, we have the horizontal projection of the cylindrical face of the stone. The radial joints J_1N_1 and Q_1M_1 are arcs of ellipses cut from the cylindrical intrados of the larger arch by the oblique planes $J'N'$ and $Q'M'$. Q_1P_1 is a right line, being the intersection of the horizontal surface of the voussoir with the larger semicylindrical arch. J_1P_1 is the projection of the arc of the circle in which the side vertical plane of the voussoir $J'P'$ intersects the larger semicylindrical arch.

114. The Directing Instruments.—Let us show the patterns of all the faces of one stone, as $E'F'G'H'I'$, in right section. To find the true length of some of the edges certain developments are necessary.

As the edges of the voussoir $E'F'G'H'I'$, parallel to the axis of the smaller arch, are all parallel to each other and horizontal, they will be projected in their true length in plan between the projection of the plane face and the projection of the cylindrical face. That is, the joint represented by F', Fig. 34, will be projected in plan (Fig. 35) in FF_1 in true length; and that represented by E' will be EE_1, and so on. The lines EF, EI, etc., Fig. 35, of the plane face of the voussoir are not shown in their true lengths, on account of the cutting plane being oblique to the axis, and also to the springing line of the arch. Also, the four edges of the cylindrical face G_1F_1, F_1E_1, E_1I_1, and I_1H_1 are arcs of curves, and are therefore not shown in their true lengths in plan. Let us now find the true lengths of the edges of the plane face of the stone and also those of the cylindrical face of the stone.

To find the true lengths of the edges of the plane face of the stone. Consider the right section $E'F'G'H'I'$ to be taken on the plane RS. In development, Fig. 38, consider the top face of the stone to be the plane of development, and that the faces to the right of G' around to I' are developed to the right of the edge $GG_1 - G'$, while the face $H'I'$ revolves to the left into the plane $G'H'$. The straight line $I'I'$, Fig. 38, is the length of the right section in

Fig. 34. Through the several points of division indefinite lines are drawn perpendicular to I'I', and on these lines lay off the distances F'F, G'G, etc., equal to f_1F, g_1G, etc., Fig. 35, the distances of the extremities of the edges of the plane face from the plane of right section RS. Join FG, GH, HI, etc., and these distances are the true lengths of the corresponding edges in Fig. 35. The curved joint of the intrados EF, Fig. 38, is found by taking one or more intermediate points, as Y'; thus, Y'Y, Fig. 38, = y_1Y in Fig. 35, and so on.

Edges of the Cylindrical Face.—The true lengths of the edges of the cylindrical face of the voussoir are found in a similar manner. Thus F'F_1, G'G_1, H'H_1, etc., Fig. 38, = f_1F_1, g_1G_1, h_1H_1, etc., Fig. 35. The lines joining the extremities of these lines are the true lengths of the edges of the cylindrical face. H_1I_1, Fig. 38, represented by H'I' — H_1I_1, Figs. 34 and 35, is an arc of the right section of the larger arch of radius RU, and is drawn with a radius = RU and laid off on the perpendicular to the chord H_1I_1 at its middle point. All the other edges except G_1H_1 are curved, and their developments will be curved, in which intermediate points must be taken as in the development of the intradosal edge of the plane face. I_1E_1 and G_1F_1, Fig. 35, are arcs of ellipses which should intersect at O_1.

Pattern of the Plane Face of the Voussoir.—The plane face of the voussoir E'F'G'H'I' is inclined to the horizontal and vertical planes, and to get its true size we revolve it about GH — G'H' into the plane of the top. This face is shown in the development in Fig. 38. The true lengths of I*i*, E*e*, etc., Fig. 35, are found on the line of slope A'L''', Fig. 36, by projecting the points across in lines parallel to A'D', and the distances intercepted on A'L''' are those required. Thus I*i*, E*e*. etc., Fig. 38, = F'''G''', E'''G''', etc., Fig. 36, the points G''' and H''' coinciding on the line L''' A', as do also Q''' and P''' of the symmetrical voussoir M'N'J'P'Q'. The intersection of the two radial joints EI and FG in the point O_2, Fig. 38, gives the center of the ellipse of which EF, Fig. 35, is a part.

Pattern of the Cylindrical Face of the Voussoir.—This is shown in Fig. 38, in which $G_1H_1 = G_1H_1$, Fig. 35; H_1I_1 = J'''Q''', Fig. 37, the true length of the circular arc of the larger arch represented by I'H' in vertical projection. The other points are found sim-

ilarly, and when joined give the pattern of the cylindrical face. This must be flexible, and when flat all of its edges are curved except H_1G_1 and H_1I_1. The patterns of any other voussoir would be found similarly.

115. Stone-cutting.—Let it be required to cut from a single block of stone the voussoir represented by $E'F'G'H'I'$ in right section. Take a block of stone which will circumscribe this right section, the length of which should not be less than the perpendicular distance from B to H_1G_1, Fig. 35. Work the top face $GHH_1G_1 - G'H'$ by use of the straight-edge and by the pattern GHH_1G_1, Fig. 38. Make the side $H'I'$ square to $H'G'$ by use of T_1, the square, and finish it by its pattern HII_1H_1, Fig. 38. Find the side $F'G'$ by the bevel T_2 and pattern FGG_1F_1, Fig. 38. Also the cylindrical intrados $E'F'$ and the face $E'I'$ by use of the arch square T_3 and the two patterns EFF_1E_1, and EE_1I_1I (Fig. 38) of the intrados and radial face $E'I'$. This completes all the faces of the stone with the exception of the two end faces. All the edges of these faces are given. The plane face can be worked by use of the straight-edge or by the pattern T_4. To determine the cylindrical face, a straight-edge kept parallel to the line $G'H'$ may be applied between the lines E_1F_1 and G_1H_1. The pattern of the face T_5 may be used to check the work. Fig. 33 in the text is a photograph of the stone cut in plaster to a scale of 1 in. to 1 ft., and exactly as outlined above.

In case the distance between the oblique plane and the intersecting arch is too great for one voussoir the courses should be cut up into stones and the joints arranged so that they break horizontally.

116. Variations.—The following examples are included in this problem:

1. Let the arch be terminated by two vertical planes; one vertical on AD and the other vertical on RS.

2. Let the arch be terminated by two vertical planes; one on AD and the second on a line parallel to AD, and at a certain distance from it.

3. Let the arch be terminated at one end by a vertical plane oblique to its axis, and at the other by a sloping plane at right angles to its axis.

117. Practical Applications.—The practical application of Example 2 is given in Art. 5, Chapter V. This is the substitute for the skew-arch with spiral courses, in which the courses are laid horizontally.

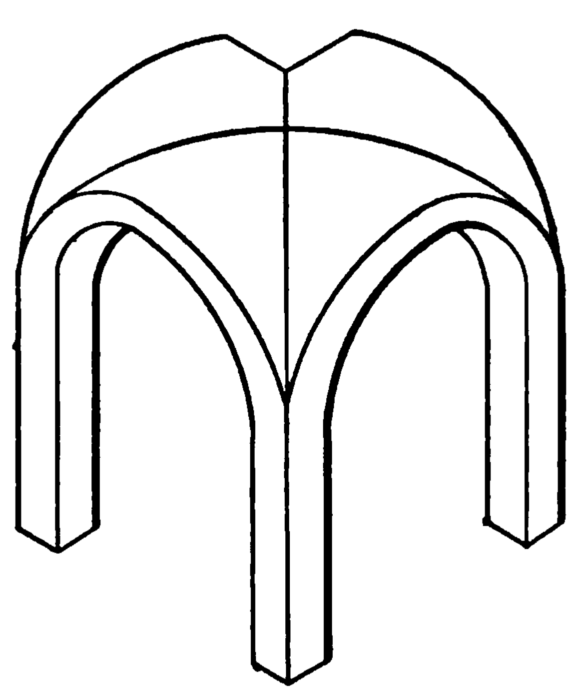
The curve of intersection of two sewers is found in a similar manner to that used in getting the intersection of the intradoses of the two semicircular arches.

ART. 6. DEFINITIONS. GROINED AND CLOISTERED ARCHES. THE GROINED ARCH.

118. Both of these arches are compound, being formed by the intersection of two cylindrical arches. The *fundamental condition* is that they have the same *rise*, but the spans may be different.

The *groined* arch is formed by removing that part of each cylinder which lies *under* the other and between their common curves of intersection. The *cloistered* arch is formed by removing those parts of each cylinder which lie *above* the other, and are above their common curves of intersection.

Figs. 38 and 39 are isometric views of the groined and cloistered arches. The *groined arch* covers the quadrangular space at which two arched passage-ways intersect. The *cloistered arch* is formed when two arches meet to form an arched covering for an area.



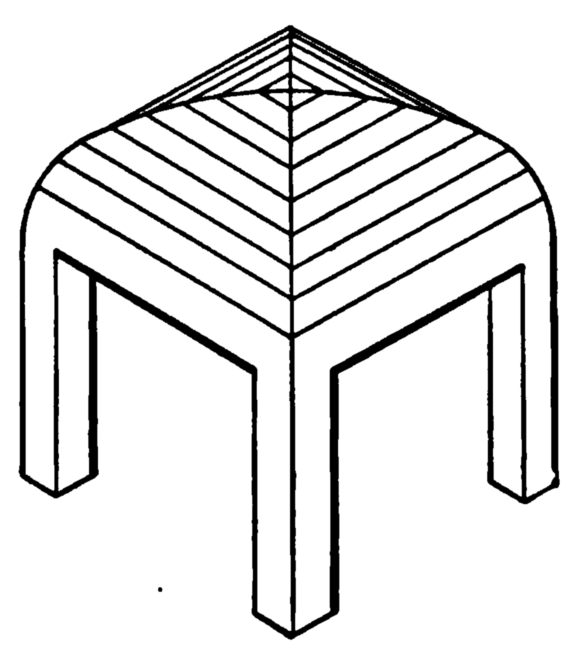


FIG. 38.—THE GROINED ARCH. FIG. 39.—THE CLOISTERED ARCH.

Two cylindrical arches having the same rise will intersect in ellipses, the horizontal projections of which will be straight lines. The curves of intersection of the two arches are called *groins* or *groin curves*. Fig. 38 shows how the groin curves are formed by

the intersection of the different elements. The arches may intersect at an oblique angle or at a right angle.

THE GROINED ARCH.

PLATE X.

119. **Problem.**—Two semicylindrical arches intersect at right angles to form a groined arch.

120. **Projections.**—B′F′C′, Fig. 39, the right section of one of the semicylinders, is a semicircle, and B″F″C″, the right section of the other, is a semiellipse. The two semicylinders have the same rise and their axes are perpendicular to each other. In the plan the joint lines of the intrados are shown in full and those of the extrados dotted, the former being the more important as the extrados is sometimes left unfinished Choose a thickness for the keystone, and let the radius of the extrados of the semicircular arch be greater than this thickness plus the radius of the intrados, that is, the radius of the extrados is below O′. The intrados, is divided into five equal parts.

Now impose the *conditions* that the bed-joints in each arch shall be normal to their soffits, and that joints of the elliptical arch shall cut the soffit at the same height above the springing plane **H**, as the corresponding joints of the circular arch.

The thickness of the spandrel-stones is the same, that is, A′J′, J′I′, A″J″, and J″I″ are equal. The joints of the circular arch radiate from O′ the center of the intrados. The right section of the voussoir of the semicircular arch is completed by passing horizontal planes through J′ and I′, cutting the radial joint O′K′ in K′ and the extrados in H′. E′K′ is the radial joint of the semicircular arch, which is, of course, normal to the soffit. Now to find the corresponding joint of the other arch.

As before mentioned, two cylindrical arches having the same rise will intersect in ellipses, the horizontal projections of which will be straight lines. The intradoses of the two arches intersect in the lines BB_1 and CC_1, and the extradoses, if cut to a curve, would intersect in the lines AD_1 and A_1D, not drawn. The method of getting the points E″, F″, etc., on the intrados of the semielliptic arch is apparent from the construction, they being the same height above **H** as E′, F′, etc., are, and on the elements through **E**, **F**, etc., parallel to the axis S″O″ of the larger arch.

To find the point in the elliptic arch corresponding to K′ in the circular one. K′E′ being radial is normal to the intrados B′F′C′ and to the tangent E′t′ at E′. Project t′ at t in the vertical plane BS of the groin. Then Et will be the horizontal projection of E′t′ considered as tangent to the groin BS at E – E′. Projecting E at E″ and t at t″ gives E″t″, the vertical projection of this tangent in the elliptic arch. E″K″, perpendicular to E″t″, is the joint in the elliptic arch. The point K″, the end of the joint, is at the same height above the springing plane as K′ is, or it is the intersection of the normal E″K″ with the top plane J″K″ of the spandrel stone.

The methods of getting the projections in plan of the voussoirs and keystone are obvious from the figure. The horizontal projections of the points N_1, O_1, etc., in the outer groin at the intersection of elements through N′, O′, N″, O″, etc., are not in a straight line with S, showing that the outer groin is not a plane curve. The curve H″G″O″ of the extrados is not an ellipse derived from H′O′ as B″S″C″ was from B′S′C′, since the two imposed conditions, that we have normal joints, and also that corresponding points in the two arches be at the same elevation above **H**, prevent this. BS‴B_1 shows the groin BSB_1 revolved about BB_1 as an axis into **H**.

The Projections of a Stone.—The stones at the intersection or groin are partly in each arch. Take the most irregular stone, L′M′N′O′P′Q′R′ in the circular arch. In the elliptic arch this is represented in vertical projection by L″M″N″O″P″Q″R″. The stone is limited in plan by $M_1m_1\,p_1D_1\,pm$. $m_1\,p_1$ and mp are planes of right section perpendicular to the axes of the two arches and taken at suitable distances from the point M_1. The horizontal courses are split up into stones so that they break joint.

121. The Directing Instruments.—These are the following: The pattern L′M′N′O′P′Q′R′ of the end of the stone in the vertical plane $m_1\,p_1$.

The pattern L″M″N″O″P″Q″R″ of the end in the elliptic arch in the vertical plane mp.

The pattern $oO_1o_1\,p_1D_1\,p$ of the plane portion of the top.

The pattern $rR_1r_1\,p_1D_1\,p$ of the plane portion of the under side.

To get the patterns of the faces, as M′N′, M″N″, M′L′, M″L″, etc., within the arches we must make two developments. Fig. 40

is the development of a part of the stone in the circular arch. o_1r_1 is the length of the right section taken on the vertical plane m_1p_1, in which o_1n_1, n_1m_1, etc., = O′N′, N′M′, etc. (Fig. 39). The other constructions are obvious from the two figures.

Fig. 41 is the development of the part of the stone in the elliptic arch, in which *or* is the length of the right section taken on the vertical plane *mp*.

In Fig. 40, $O_1o_1n_1N_1$ is the pattern of the face $O'N' - o_1n_1N_1O_1$ in the circular arch, which must be flexible; $n_1m_1M_1N_1$ is the pattern of the radial bed $N'M' - n_1m_1M_1N_1$; $m_1l_1L_1M_1$ is the pattern of the cylindrical intrados $M'L' - m_1l_1L_1M_1$, which must be flexible; and $l_1r_1R_1L_1$ is the pattern of the radial bed $L'R' - l_1r_1R_1L_1$.

The analogous patterns of the faces of the part of the stone in the elliptic arch are shown in Fig. 41. The right section-bevels shown on the vertical elevations will also be of assistance in cutting the stones.

122. Stone-cutting.—Choose a block of stone in the plan of which $M_1m_1p_1D_1pm$ may be inscribed, and whose thickness is equal to the distance of N′ from a horizontal plane through L′. Work the end of the stone in the plane m_1p_1 by means of the pattern L′M′N′O′P′Q′R′. Work the top, bottom, and side faces of the stone by use of the square and the patterns of those faces previously given. The other faces of the stone are gradually worked off by use of the patterns in Figs. 40 and 41 and the two arch squares.

123. Exercises.—1. Draw an isometric of the keystone.

2. Draw an isometric of the stone L′M′N′O′P′Q′R′.

3. Let the two arches intersect at an oblique angle.

4. Let the two arches be semicircular.

5. Let both arches be semielliptic.

124. Practical Applications.—Groined elliptic arches are now being used for the covering of reservoirs and filter-galleries, and they offer many advantages over other forms of roof-coverings. Examples of groined elliptic arches of composite brick and concrete are those of the covered filters at Ashland, Wis., and Somersworth, N. H. Those of concrete alone are of the Wellesley and Clinton (Mass.) reservoirs, and of the Albany (N. Y.) Waterworks. The student is referred to the following articles for more

detailed information in regard to the use of elliptic arches of brick and concrete as reservoir-covers.

1. Metcalf. On the Groined Arch as a Covering for Reservoirs and Sand Filters: Its Strength and Volume. Trans. Am. Soc. C. E., 1900, XLIII. 37.

2. Hazen. On the Albany Water Filtration Plant. Trans. Am. Soc. C. E., 1900, XLIII. 244.

3. Freeman. On Covered Reservoirs and their Designs. Jour. Assoc. Eng. Soc., July, 1899, XXIII. 1.

4. The New Clear-water Reservoir at Louisville, Ky. *Eng. News*, 1901, XLV. 34.

ART. 7. THE CLOISTERED ARCH.

PLATE X.

125. Problem.—Two semicylindrical arches intersect at right angles to form a cloistered arch.

126. Projections.—The right section of one arch B′F′C′, Fig. 42, is a semicircle, and B″F″C″, that of the other, is a semi-ellipse. Neither arch extends beyond the other. The rise of the two arches is the same, and let there be five voussoirs. The center of the extrados of the circular arch is at O_1 below O′. In the first method of construction the extrados of the elliptic arch is an ellipse parallel to that of the intrados. The lower voussoir is A′B′E′H′I′, the exterior face A′I′ of which is vertical. The exterior lines of the cloistered arch in plan are ADD_1A_1, and BCB_1C_1 are the interior lines of the top of the walls. The semi-circular arch springs from the lines BC_1 and CB_1, and the semi-elliptic arch springs from the lines BC and C_1B_1. The lines BB_1 and CC_1 are the projections of the groins of the intrados. $mnNn_1m_1M$ is the plan of the joint M′N′ shown in right sections at M′N′ and M″N″; $mpPp_1m_1M$ is the plan of the cylindrical intrados, and so on. The points M, N, etc., are the intersections of elements through M′ and M″, N′ and N″, etc., mo and m_1o_1 are the traces of planes of right section perpendicular to the axes of the two arches and taken at a convenient distance from M. The radial joints in the elliptic arch are obtained as in the groined arch, that is, they are tangents to the ellipses at the several points E″, F″, etc. MN not being in a straight line with S shows that the outer groin is not a plane curve.

If it is desirable that the outer groin be an elliptical curve coinciding with the inner groin in plan, that is, being in the same vertical plane, the following method is pursued. Take the joint E′H′ as an illustration. The point H′ will be projected at J on B_1B produced, instead of at H as before. J will be projected in the extrados of the elliptic arch at the same height above **H** as H′ is. Other points similarly found will give the semiellipse G″K″J″. Produce the joint E″H″ until it intersects this new extrados in the point K″.

This construction gives greater radial thickness toward the springing line of the elliptic arch, which is desirable. If the radius O_1T' does not exceed a certain limit with respect to O′S′ and S′T′, the radial joint E″H″ will be less than the thickness of the arch at the crown, which will not be a stable construction.

In plan the joints of the intrados are shown in full as in the last problem.

127. The Directing Instruments and Stone-cutting. — The directing instruments are constructed as in the groined arch, the two developments giving the true lengths of the joints. Figs. 43 and 44 are these developments. The stones can be cut in a similar manner to those in the groined arch.

128. The Groined and Cloistered, or Elbow Arch.—A sketch of this is shown in Fig. 45. It is a combination of the groined and cloistered arches, and the directing instruments are obtained in a manner similar to those in these cases.

129. Exercises.—1. Construct an isometric of the keystone.

2. Let the two arches be elliptical with equal rise and span.

3. Let the two arches be circular.

Art. 8.—The Descending Arch.

Plate XI.

A *descending arch* is one whose axis is inclined to the horizontal plane. It is also sometimes called *rampant*.

130. Problem.—An arch leads from a street into an underground railway. The axis of the arch is oblique to that of the railway. This case is a variation of the problem in Art. 5, where the arch is terminated at one end by a vertical plane, and at the other end by a horizontal arch whose axis and elements are parallel

to the vertical plane of the end. The case is taken where the axis and elements are oblique to both the vertical plane and to the horizontal plane, the simple case being where the axes of the arches are at right angles to each other, that of the smaller being inclined to the horizontal plane.

131. **Projections.**—B′E′C′ (Fig. 46) is a *semicircle* and is the oblique section of the arch by the vertical plane of the end. The lowest element of the horizontal semicylinder whose axis is TU is projected in *ad*. This element lies in a horizontal plane at a distance D′D″ below A′D′. The lowest elements of the arch through A′, B′, C′, and D′ intersect the line *ad*. The voussoirs in this case are formed as usual, there being only three for simplicity.

To find the true lengths of the edges of the voussoirs, it will be necessary to find their projections on a plane parallel to them. Let this plane be taken as the vertical one, whose horizontal trace is D′T. Suppose this plane is revolved about its trace D′T into the horizontal plane. D″*d* will be the projection of the axis and lowest elements on this plane, and the other edges will all be parallel to it, the end of the arch at A′D′ being the distance D′D″ higher than that at *ad*. The projection of the head of the arch on the revolved plane will be in the line D′K″, perpendicular to *d*D′.

The semiellipses cut from the larger semicylinder by the vertical planes through the elements will have *d*T for their semimajor axis and the radius of the cylinder for their semiminor axis. These are all projected upon the vertical side plane whose trace is D′T in one semiellipse, and *d*TV will be the revolved position of one half of this semiellipse on the horizontal plane. That is, provided the points are projected in lines parallel to A′D′, and not in lines perpendicular to the plane as they are usually projected. By this method the relative position of the lines is not changed, while with the perpendicular lines a separate construction would be necesary for each element.

Now the true lengths of the elements, or joints, of the voussoir along the axis are the distances intercepted between the line D′K″ and the ellipse *d*TV. Thus to find the joint projected in H′, set off from D″ on D″K″ the distance D″H″ equal to the height of H′ above A′D′, and H″H‴, parallel to D″*d*, will be the true length of the joint represented by H′. Other joints are found in a sim-

ilar manner. It now remains to find the soffit and the joints in the plane and circular faces in their true dimensions, and for this it will be necessary to find the curve of right section.

Right Section.—YZ perpendicular to the axis $O'o$, and ZX'' perpendicular to its projection $D''d$ on the vertical side plane, are the traces of the plane of right section. To construct the curve of right section we must find the projections on the vertical side plane of the points in which the elements of the soffit cut the plane of right section, and then revolve these points onto **H**. This construction is as follows: The vertical plane which contains the element through H', for example, will cut the plane of right section in a line parallel to ZX'', its trace on the vertical side plane. The point h_2, where the horizontal trace YZ of the plane of right section and the horizontal trace Hh of the vertical plane through the element H' intersect, will be one point in the required line. This point being in **H** will be projected at h' in the line $D'd$ of the vertical side plane, and the line through h' parallel to ZX'' will be the projection of the line cut from the plane of right section by the vertical plane through the element H'. The point h'' where this line cuts $H''H'''$, the projection of the element through H' on the side vertical plane, will be the projection of one point of the curve of right section. Other points similarly found and consecutively joined will give the projection of the curve of right section on the vertical side plane. The true distances of any points of the horizontal semicylinder and the vertical end plane from the curve of right section may be found from this figure, since the elements are here projected in their true lengths. To find the curve of right section itself we revolve its projection on the vertical side plane around the trace YZ into **H**. The point projected in h'', for example, will be found at h_1, at a distance h_2h_1 from YZ equal to the distance $h'h''$. Other points similarly found and joined give the true size of the curve of right section. The line a_1d_1, corresponding to ZX'' in the side projection, will be the diameter of the curve of right section.

We now have the true size of the curve of right section, and also the distances of points in the vertical end plane and in the cylindrical face, from this curve. The soffit may be developed as usual (Fig. 47), the explanation of the construction and use of which will be given in obtaining the directing instruments.

Remark.—The student will be assisted in his understanding of the above constructions if he will construct an oblique cylinder of paper, elevate one end of it and locate a plane of right section, and then revolve it as described. He will thus readily perceive why the trace of the plane of right section and the diameter of the curve of right section do not coincide in plan.

132. **The Directing Instruments.**—Let us take one voussoir as an example, as C′D′J′I′H′. In order to find the patterns of some of the faces, certain developments are necessary, as follows (Fig. 47): Draw a line a_1d_1 and lay down upon it the true length of the curve of right section $b_1e_1h_1c_1$, as shown in Fig. 46. Through the points of division draw lines perpendicular to a_1d_1, and set off on them above and below a_1d_1 the distances h_1H′, h_1H‴, and e_1E′, e_1E‴, etc., respectively equal to h''H″, h''H‴, and e''H″, e''H‴, etc., Fig. 46. The curves B′E′H′C′ and bE″E‴H‴C‴ will be the developments of the intersection of the soffit with the end plane and the intersection of the soffit with the semicylinder. Now to construct the pattern of the radial joint, of which H′I′ is the vertical projection. Set off h_1i_1 on $a_1d_1 = h_1i_1$, Fig. 46 and through i_1 draw i_1I′ perpendicular to a_1d_1. Set off on it i_1I′ and i_1I‴, respectively equal to i''I″, i''I‴, Fig. 46. Joining H′I′ by a straight line and H‴I‴ by a curved line, the figure obtained is the pattern of the required face. The faces of the other stones are obtained in a similar manner. The method of finding an intermediate point on the curve H‴I‴ is evident from the construction lines in the two figures. H′C′cH‴ is the pattern of the soffit of the stone considered.

Now the patterns of the other faces of the stone in question are as follows:

The pattern of the right section is $c_1d_1j_1i_1h_1$.

The pattern of the top face is a parallelogram of width i_1j_1 and length I″I‴, two sides of which will be I″I‴ and D′I.

The pattern of the vertical side of the stone on J′D′ is of perpendicular width, d_1j_1, bottom length of D′d, and top length of I″I‴. One end of this face is the vertical line D′J′, and the other the arc di_3 of dW, corresponding to dI‴ of dV.

The pattern of the plane end of the stone is H′I′J′D′C′.

The pattern of the opposite cylindrical end differs from this in that D′J′ would be replaced by the development of the arc di_3;

and HH′, by that part of dW corresponding to dH‴. The developed joint H′I′ would be curved and found by use of an intermediate point as in other preceding problems.

Besides these patterns, bevels set to the angles $j_1i_1h_1$, $d_1j_1i_1$, and I‴I″D′, will be of service in working the stone.

133. Stone-cutting.—Two methods of working a stone may be used: first, the method by squaring; and secondly, the method of oblique-angled bevels.

Method by Squaring.—Choose a block of stone capable of containing the right section, $e_1d_1j_1i_1h_1$, and sufficient in length. Make all the faces square with the right section, and mark their edges by use of their patterns previously given. We then have all the edges of the two ends, and they may be worked by applying a straight-edge to them in a direction parallel to A′D′. This method of cutting the stone is accurate, but is wasteful of material and labor, and the next method is preferable.

Method by Bevels.—With a suitable block of stone work the vertical side of the stone, D′J′, that being the largest, by use of its pattern. Work the top face square with this face, the arm of the square being guided by a bevel set to the true angle at the point D′ in the pattern of the top face, this face being a parallelogram. Complete the face by use of its pattern. Work the under face similarly, and the radial bed on H′I′ by use of the bevel $j_1i_1h_1$ held perpendicular to the top edge. By use of the bevel I‴I″D′ work the plane end of the stone. From the plane end the other faces and the cylindrical end may be easily worked, the distances of all points from the plane being found from the side elevation.

134. Exercises.—1. Take the simple case where aA′ is perpendicular to A′D′.

2. Cut a voussoir out of plaster.

3. Construct the patterns for the keystone.

Art. 9. High Bridge Pier.

Plates XII and XIII.—Piers of the Glasgow Bridge over the Missouri River.*

135. This style of pier has been much used in this country for bridges, among which may be noted the Memphis bridge over the

* Information from the *Jour. W. Soc. Eng.*, vol. vi. p. 104, and by correspondence with Mr. H. P. Boardman.

Mississippi River, the Cairo bridge over the Ohio, and a large number over the Missouri River.

Plate XII gives an end elevation, a side elevation showing thickness and numbering of courses, and also the general dimensions of the courses of Pier 4.

As will be noted from the drawings the pier is a symmetrical pier with curved pointed ends from bottom to the starling coping just above extreme high water, and with semicircular ends above that. The tabulated general dimensions are given in the plate, which the student will be able to understand by referring to the plans of the several courses.

The distance between shoulder-points, or points of tangency, between the straight sides and the curved ends is constant, and equals 25 feet for all courses. The centers for the end curves of the courses below the starling coping are at the constant distance of 5 feet 3 inches from the axis of the pier.

Plate XIII is a sample of the detail plans of the courses, and gives the method of marking the stones. The following method was used in detailing the courses:

"On a blue-print of the general elevation (Plate XII) the vertical joints were marked off between the shoulder-points, breaking joints at least 15 inches, and allowing $\frac{1}{2}$ inch for all joints.

"The curved end of each course was drawn to a scale of $1\frac{1}{2}$ inches to the foot, and the chord lengths for the different stones determined by scale, two courses being plotted on the same sheet and different-colored ink used to distinguish them. In the case of two or three courses this method was checked by computation, making use of the angle θ, and the maximum error by method of scaling from shoulder to shoulder around the point found to be about $\frac{1}{4}$ inch. The stones diametrically opposite in any course are alike in dimensions."

The following extracts describe the kind of material used in the piers: "The interior or backing of these piers is concrete, with exception of the belt and coping courses, which are of dimension stone throughout.

"The top coping and starling copings at both up- and downstream ends are of granite for all piers. In Piers 3 and 4, the upstream stones from shoulder to point are granite for all courses

below the starling coping." All other stone in the Piers was Bedford limestone. The granite used was Lithonia (Ga.) granite.

Some interesting points upon cutting the stone are as follows: Templates were used for cutting all the curved face stones. The contractor was allowed to vary the horizontal face dimension two or three inches to save waste of stone, provided it did not interfere with the required breaking of joints, and provided the variation was corrected in other stones of the same course, so that total dimensions between controlling points should be correct.

The Bedford stone is practically without stratification and very easily worked, and where possible the stones are sawed to shape.

"The exposed faces of all granite stones in the copings are bush-hammered, and the granite cutwater below starling copings is fine-pointed. The Bedford masonry is rock-faced, and a three-inch chisel-draft was cut at shoulder-lines around the lower edge of the projecting belt course and on the down-stream angle below the starling coping."

Other points with regard to the courses are given in the plates.

Art. 10. Arch Culverts.

STONE ARCH CULVERT.

Plate XIV.

136. This plate shows a common form of arch culvert. The plate has sufficient general dimensions on it, to enable the culvert to be built with a set of specifications. The following are points to be noted: Width of roadbed is 14 ft. The back faces of the steps of the wing wall conform to the slope of the earthwork, which is $1\frac{1}{2}$ to 1. Each step projects beyond the face of the wall and under the step above it. The batter of the front face of the wing wall is 2 inches to 1 foot.

137. Masonry for arch culverts is sometimes divided into first- and second-class masonry. (§§ 36–40.) Many railroads give a general specification for arch masonry, of which the following is a good example:

"Face walls, bench walls, piers, spandrels, and parapets will be built under the Specifications for Bridge Masonry (1st class), but will be measured up with the arch sheeting and voussoirs, and the entire work paid for at one price. The arch stones must be of full size throughout. They will be not less than twelve

inches face on intrados, nor less than three feet long. Number of courses and depth of arch stone will be marked on the drawings. Both sides of sheeting to be carried up together. In case of two or more arches in one structure they will all be carried up together. Backing will consist of large stones, as specified for Bridge Masonry, shaped to fit arch and laid in full beds of mortar. Face of ring stones to be pitched unless otherwise specified; no projections over three inches being allowed beyond pitch-lines. Soffit of arch to be fine-pointed. Joints of sheeting and voussoirs will not exceed ⅜ of an inch. Bond to be not less than twelve inches. Backing must be bonded to the spandrels." *

PLATE XV.—STANDARD 10 × 10 FT. CONCRETE ARCH CULVERT, NEW YORK CENTRAL & HUDSON RIVER R. R.

138. In view of the fact that concrete has, or is rapidly taking the place of stone for this class of work, it was thought best to include the design of a concrete arch culvert.

The plate is quite fully dimensioned. Note the batter and general dimensions of the wing walls, and the different classes of concrete used, and the proportions of each.

139. Among articles on the design and construction of concrete arch culverts the following are deserving of mention:

1. Concrete Arch at Sharpsville, Pa., on the Erie and Pittsburg Division of the Pennsylvania Lines West of Pittsburg. Semicircular arch of 15 ft. radius. *R. R. Gazette*, 1900, XXXII. 750.

2. Concrete Bridges and Culverts on the Illinois Central R. R. A 40 ft. arch and others. *Eng. News*, 1901, XLVI. 43.

3. Standard Concrete Arch Culvert for Porto Rico Highways. A flat arch of 8 ft. span. *Eng. News*, 1901, XLV. 202.

ART. 11. MASONRY ARCH BRIDGES.

PLATE XVI AND FIG. 40.—THE BELLEFIELD ARCH BRIDGE. †

140. The Bellefield Arch Bridge at the entrance to Shenley Park, Pittsburg, is one of the most elaborate stone bridges in this country.

* Specifications of the Pennsylvania Lines West of Pittsburg, 1898.

† *Eng. Record*, June 9, 1900, vol. XLI. 540, and *Eng. News*, June 22, 1899, vol. XLI. 391.

FIG. 40.—THE BELLEFIELD ARCH BRIDGE

[*To face page* 76]

FIG. 41 — THE WEST BRIDGE, ELYRIA, OHIO.

[*To face page* 77.]

It is a segmental arch of 150 foot span, and 36 ft. 8 in. rise. It is 82 feet wide across the soffit, with a 59-foot roadway and two 10-foot sidewalks. Plate XVI gives some of the details of this arch.

The depth of ring stones at the crown is 4 feet, gradually increasing to 6 feet at the springing lines. Both the sheeting and ring stones were cut with $\frac{1}{4}$ in. joints, rough-pointed on the soffit, and made to break joints everywhere not less than 18 inches. The foundations were carried down to solid rock, upon which were laid the three footing courses, the plans and sections of which are given in the plate.

The extrados of the arch was left as rough as possible and covered with concrete. The thickness of concrete diminishes from 4 ft. at the springing lines to 18 inches at points 30.5 feet each side of the center of the span. At these points it was filled in level to the sub-grade, a maximum thickness of 8 ft., and at the crown a minimum thickness of 5 ft.

A retaining wall was built on this concrete backing in line with the face of the abutments and carried up to sub-grade. Between these retaining walls, and on the concrete backing, were built 27-inch spandrel walls forming openings 8 ft. 6 in. by 9 ft. 6 in. The openings between the spandrel walls were spanned by 13 in. brick arches. The space above these brick arches was filled in with natural cement concrete up to the sub-grade of the roadway.

The information for this description was obtained from the periodicals before mentioned, and the half-tone of the arch is from Fowler's "Engineering Studies," Part I.

FIG. 41.—THE WEST BRIDGE, ELYRIA, OHIO.

141. This illustration, taken from Fowler's "Engineering Studies," Part I, is given to show the student how the courses and arch stones are arranged with respect to bond, etc.

The dimensions of the arch are as follows: Span 112 feet, rise 19 feet 6 inches, width across the arch ring 38 feet, and width across the top 44 feet. The skew-backs are from 4 to 8 feet above the bed of the stream. The arch ring has a depth at the keystone of 3 feet 6 inches.

The arch is constructed of first-class rock-faced masonry, the stone being Elyria sandstone.

FIG. 42.—THE PELHAM ARCH.*

142. This arch is located on the New York Division of the New York, New Haven & Hartford R. R., at Pelham, N. Y. (formerly Pelhamville). It is a five-center arch of 40 ft. span, with a rise of 10 ft. The intrados corresponds closely to an ellipse, the radii of the three arcs being respectively 5 ft. 7¼ in., 20 ft., and 40 ft. A joint was placed at each change of curvature. The geometry of the oval was given in a previous problem. (§ 105.) The sheeting and ring stones were all cut in the quarry. The joints are ¼ in. The surface of the ring stones is rock-faced, with no projection exceeding 1½ in., with a 1 in. chisel draft along the edges. The intrados is bush-hammered. The stone is gneiss, with the exception of the keystones and coping, which are of Connecticut granite and bluestone.

By a careful inspection of the figure many points on construction may be gained.

**Eng. News*, 1895, XXXIII. 34. Photograph from Mr. H. B. Seaman, M. Am. Soc. C. E.

Fig. 42.—The Pelham Arch.

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CHAPTER V.

THE OBLIQUE OR SKEW ARCH.

ART. 1. DEFINITIONS. MECHANICS OF THE ARCH. METHODS OF CONSTRUCTION. ELEMENTARY PRINCIPLES OF THE HELICOIDAL METHOD.

143. An *oblique* or *skew* arch is one in which the heads are oblique to the axis. The *angle of skew* is the angle at which the face of the arch is askew from its normal position, or the angle which the *face* makes with a *plane normal* to the *axis*. The *angle of obliquity* is the *acute* angle which the *axis* makes with the *plane* of either *face* of the arch. Thus in Fig. 43, the angle of skew is the angle BAH (= angle GEF), while the angle of obliquity is the angle FEB. The angles are complements of each other. The terms *angle* of *skew* and *angle* of *obliquity* have been used interchangeably by many writers on the skew-arch. Others have incorrectly called the angle of obliquity the angle of skew, and *vice versa*. In this work the correct definitions as given above will be used. Accordingly the angle of skew of a right arch by this definition is 0°, as it should be.

MECHANICS OF THE ARCH.

144. In a right arch the "thrusts" or "lines of pressure" are assumed to act in planes parallel to the faces. The weight of one half with its superincumbent load is supported by that of the other half, the two being supported at the ends by the abutments.

When the faces are not at right angles to the axis, or the arch is a skew-arch, if the lines of pressure are assumed to act in planes perpendicular to the axis, the portions AEI and AEKJ, Fig. 43, are imperfectly supported. If the pressures are assumed to act in planes parallel to the faces, these lines of pressures will make acute angles with the coursing joints and there will be components

acting parallel to the joints which will tend to produce slipping. If the angle of skew is small, this slipping tendency is slight and is easily resisted by the friction of the joints and adhesion of the mortar. As the angle of skew increases the tendency to slipping is increased and may cause failure.

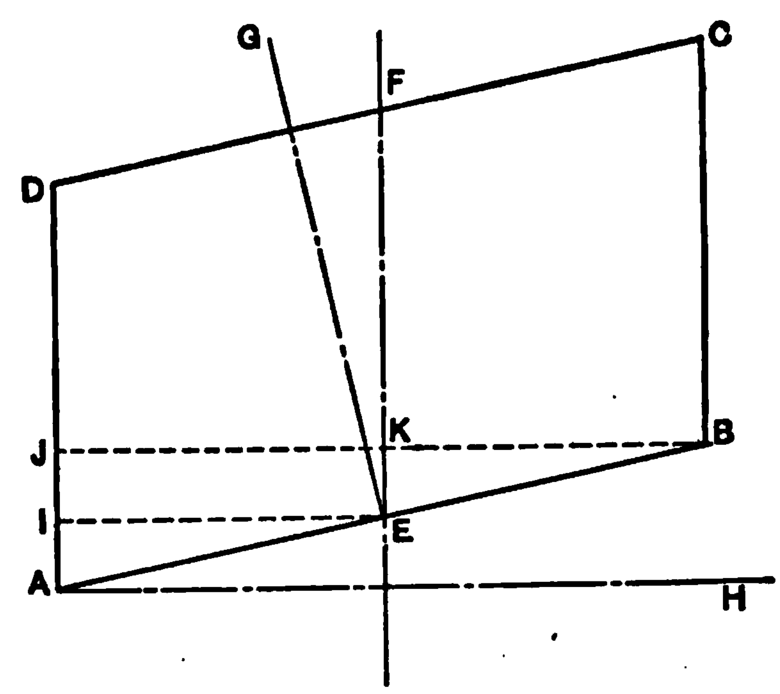


FIG. 43.

The problem in the design of skew-arches is so to arrange the joints that the pressures shall be practically perpendicular to the joints.

We will now briefly outline the different methods by which skew-arches are constructed.

METHODS.

144. **First.**—The skew-arch, with courses parallel to the axis of the arch, as outlined in the previous paragraph and illustrated by the example in Art. 5 of this chapter. This form of arch is called the "false" skew.

Second.—The skew-arch with ribs, as illustrated by the example in Art. 6. This arch is composed of a number of small right arches, which project beyond each other in opposite directions on the two sides, so that the proper skew is obtained, and which are fastened together by wrought-iron U-clamps at points on the extrados.

Third.—Skew-arches constructed with spiral courses. The joints extending along the arch are called *longitudinal* or *coursing* joints, and those across the arch are called *transverse* or *heading* joints. The former divide the arch into courses, and the latter divide the courses into stones.

From what has been said it is evident that it is desirable in an oblique arch that the thrust should be carried to the abutments in planes parallel to the oblique faces of the arch, or as nearly so as is possible, and that this cannot be obtained when the coursing joints are parallel to the axis of the arch. The *perfect* design of a skew-arch is one where the *coursing beds* are normal to the oblique faces of the arch wherever they come in contact with them. The form of arch constructed in this manner is called the *equilibrated* arch. On account of the difficulty in attaining this, some method which closely approximates the equilibrated arch is used. The three methods used are the *Helicoidal,* the *Logarithmic,* and the *Corne de Vache,* or *Cow's-Horn.* Briefly stated the main points of difference in the three methods are as follows:

Returning to Fig. 43; suppose lines drawn parallel to the face of the arch. These will also represent traces of vertical planes parallel to the face of the arch, and they cut ellipses from the arch. The coursing beds should be normal to these curves both on the intrados and on the extrados of the arch, wherever they come in contact with them. As the curves are ellipses, their developments are curved and the coursing joints should be perpendicular to these parallel curves both on the intradosal and extradosal developments. In the logarithmic method they are perpendicular to the developed curves on the intrados. In the helicoidal method the coursing beds are perpendicular to the line joining the extremities of the developed face line of the intrados. In the *Corne de Vache,* or *Cow's-Horn* method, the intrados of the arch is a warped surface. In the helicoidal method all voussoirs of the same length are exactly alike, except those in the arch face, while in the other methods the courses vary in thickness across the arch, and each stone is always different from the next one to it in the same course.

We will first describe as briefly as possible the helicoidal method, which is the one used principally, and then merely state the peculiarities of the other methods and refer the student to works where they are treated more fully. We will also illustrate the "false" skew by an example, and the skew-arch with ribs by an example.

THE HELICOIDAL METHOD. ELEMENTARY PRINCIPLES.

145. A *helix* is a curve generated by a point having two *simultaneous* motions with respect to an axis; one motion around that axis and the other parallel to it. When these motions are uniform the curve generated is a *common helix,* or simply a helix. This curve will lie on the surface of a cylinder the radius of which is equal to the perpendicular distance from the point to the axis. Thus in Fig. 44, A′B′C′ is the elevation, and ACDE is the plan of a semicylinder with radius O′A′, and length AE. Divide A′B′C′ and AE into the same number of equal parts —nine in this case—and through the points of division 1″, 2″, 3″, 4″, etc., of AE draw lines parallel to AC, the face of the cylinder, to meet lines drawn through the corresponding points 1′, 2′, 3′, 4′, etc., of A′B′C′ and parallel to AE. The curve A4D, joining the successive points of intersection of these lines, is the horizontal projection of a semihelix.

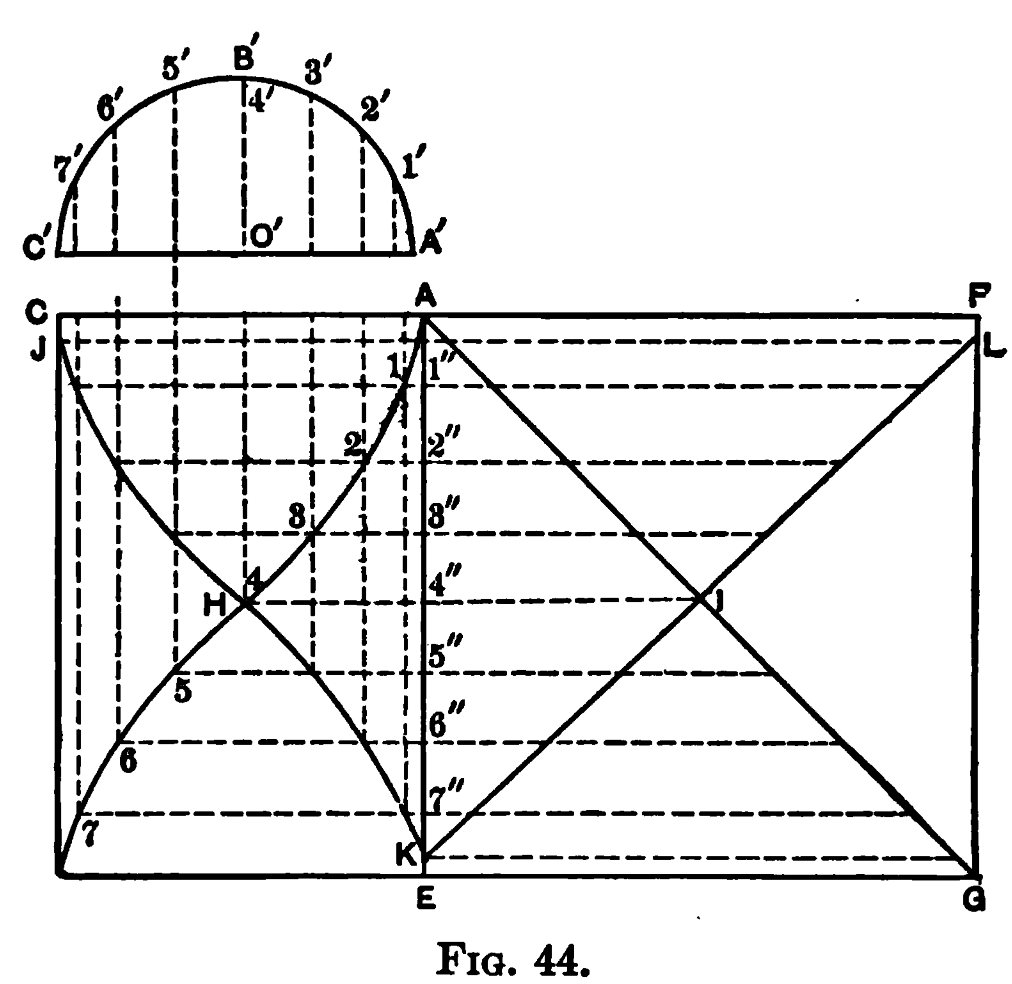


FIG. 44.

Now, if we consider the semicylinder as the soffit of a right arch, the development of it will be AEGF, in which AF perpendicular to AE is equal to the curve of right section A′B′C′. Then AG will be the development of the semihelix A4D, and is a straight line. From this development we can find the location in plan of a semihelix perpendicular to the helix at its middle point

H. This semihelix will, in development, be perpendicular to AG at its middle point I. The method of obtaining the plan of the helix is evident from the figure.

The distance which the point generating the helix moves along the axis of the cylinder in one *complete* revolution of the cylinder is called the *pitch* of the helix, or *axial length.*

Remark.—The student may see the exact nature of a helix by comparison with the thread of a screw. If the cylinder were surrounded with any number of spirals, all being similar and equal, the entire projection of a screw would be obtained.

146. Helicoidal Surface.—Now if we suppose a line to move along the helix DA, always remaining perpendicular to the axis of the cylinder and radiating from it, the surface generated will be a helicoidal surface. Thus in Fig. 45, F′G′H′ is the elevation

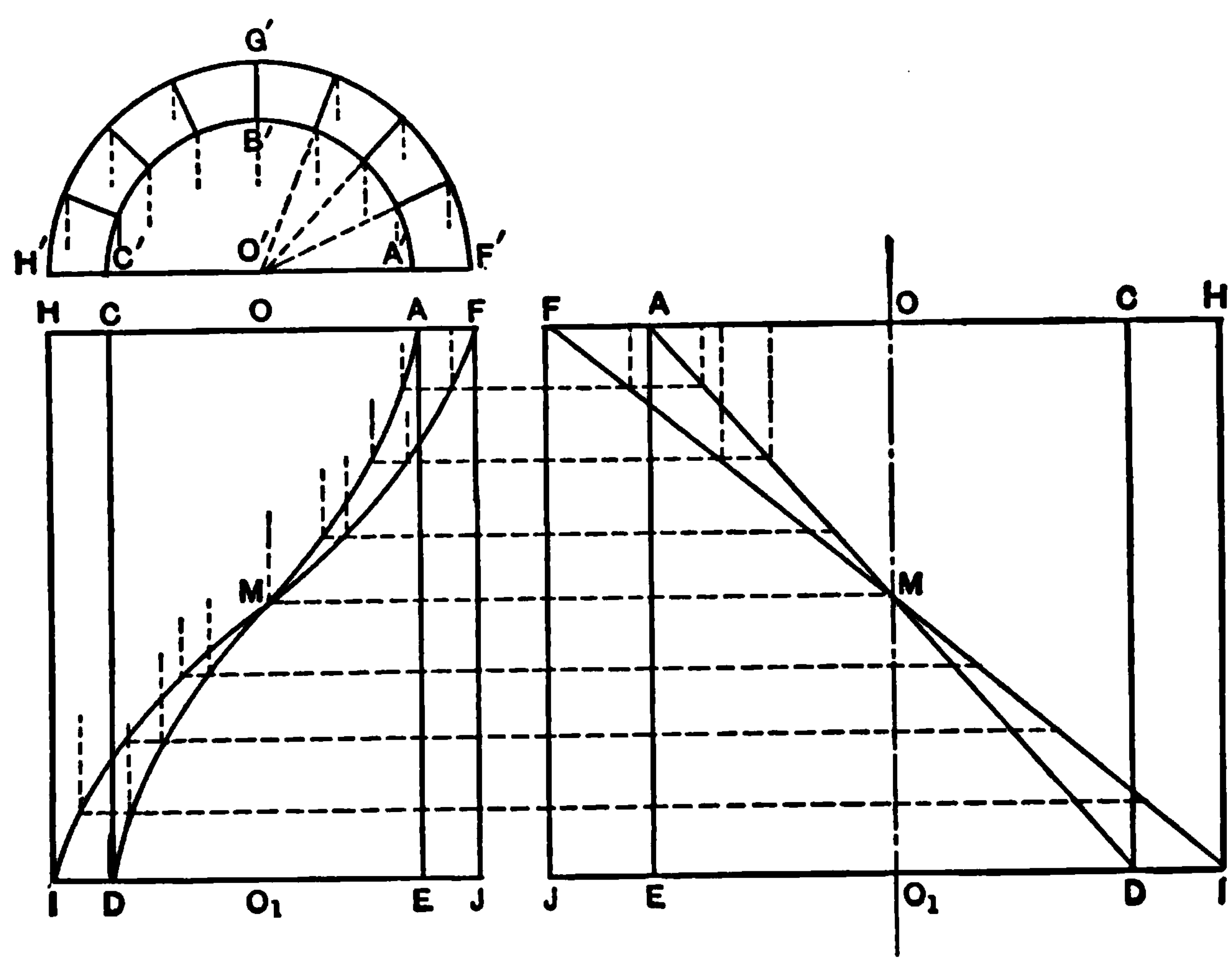


FIG. 45.

of the extrados of a right arch of thickness A′F′, the plan of which is FHIJ. ACDE and FHIJ in the right-hand part of the figure are the intradosal and extradosal developments of the arch, both symmetrical with respect to the axis OO_1. The development of the intradosal helix is AMD, and that of the extradosal helix is FMI. The horizontal projections of these helices are the curves AMD and FMI, determined from A′B′C′ and AE, and F′G′H′ and FJ, as in the previous case.

The surface included between the curves AMD and FMI is a helicoidal surface, generated by a straight line, as AF, equal to the thickness of the arch, moving along the arch always and perpendicular to the axis OO_1 and radiating from it. The surface is a warped surface.

In the helicoidal method the beds of the coursing joints are helicoidal surfaces generated as outlined above, while the beds of the heading joints are also helicoidal surfaces at right angles to them. The student may see the exact nature of a helicoidal surface by comparison to a square-threaded screw. He should thoroughly master these elementary principles before proceeding with the next article.

Art. 2. A Helicoidal Oblique Arch.

Plates XVII* and XVIII.

147. As an example of an arch built on the helicoidal system, we will take the dimensions of the main span of the skew-arch over Sixth St., Reading, Pa.* This arch is taken as it is one of the best examples of a helicoidal oblique arch in this country, built entirely of stone. It is also a segmental arch, which case would be more likely to occur in the experience of the engineer than the full-centered. The directing instruments for the segmental and full-centered arches are obtained in the same manner, a few of the equations being different on account of the soffit in the former being the segment of a circle, instead of a semicircle, as in the latter. The student should have no difficulty in making the required changes in the formulas for the design of a full-centered arch, if called upon to do so.

An oblique arch on the helicoidal method may be designed almost entirely without the aid of drawings, but in this case, in order to give the student a clearer understanding of the problem, the drawings will be made in connection with the calculations. It is evident that in the preparation of the working drawings for an oblique arch a great deal of projection and transferrence of

*Osborne's "Engineering Structures," Part I. This arch is still standing (July, 1902), according to Mr. T. R. Crowell, City Eng., of Lebanon, Pa. It was not possible to obtain a photograph of the arch without considerable difficulty, as a part of the soffit on each side is obscured by a wooden floater covered with advertising matter.

points and lines is necessary, and that it is almost impossible to do this at a scale large enough to be safe to take the measurements from the drawing in order to construct the arch. In most cases the calculations are first made, and then the drawings are prepared mainly for the purpose of making the method of construction clearer, and for convenience in having a record of the work. The directing instruments are obtained entirely from the calculations.

148. The dimensions of the arch taken as an example are as follows, by reference to the figures in Plate XVII:

AB $= s =$ direct span $= 30$ ft.
ME $= h =$ rise $= 10$ ft.
NA $= e =$ thickness of voussoirs $= 2$ ft. 4 in.
Angle BDA $=$ angle of obliquity $= \theta = 48° \; 30'$.
DL $= b =$ width of soffit on the square $= 29.55$ ft.

From these five governing quantities the following quantities are derived:

AX $=$ R $=$ radius of intrados $= \dfrac{h^2 + s^2}{2h} =$ 16 ft. 3 in.
AD $=$ oblique span $= s \,.\, \text{cosec}\; \theta = 30 \times 1.3351924 = 40.056$.
BD $=$ obliquity of arch $= s \,.\, \cot \theta = 30 \times .88473 = 26.54$.

The length of the arc AEB of the square section is found as follows: sin angle AXM $= \dfrac{\text{AM}}{\text{AX}} = \dfrac{15}{16.25}$, and angle AXM therefore $= 67° \; 22' \; 48''$, and angle AXB $= 134° \; 45' \; 36''$. Length of arc AEB accordingly $= n \times \text{R} \times .017453 = 38.22$.

Length of square section of extrados $= n\,(\text{R} + e)\; .017453 = 43.70$, where $n =$ the number of degrees in angle AXB $= 134.76°$.

Tan $\angle$ RAF $=$ tan of intradosal angle $=$ tan $\beta = \dfrac{\text{BD}}{\text{AR}} = \dfrac{26.54}{38.22}$, $\beta = 34° \; 47'$, to the nearest minute.

Tan $\phi =$ tan extradosal angle $= \dfrac{\text{R} + e}{\text{R}}$ tan $\beta = 38° \; 27'$, to the nearest minute.

Twisting rule angle $= \phi - \beta = 3° \; 40'$.
AF $=$ length of heading spiral $=$ RA sec $\beta = 46.535$.
AH $=$ length of impost $= b \,.\, \text{cosec}\; \theta = 39.46$.

Let the number of voussoirs be 31, then the width of each voussoir $= \frac{46.535}{31} = 1.501$ ft.

GK = Divergence of courses $= b \,.\, \text{cosec}\ \theta \sin \beta = 22.511$. Number of courses intersected by spiral off impost $= \frac{22.511}{1.501} = 15$.

Now, having proceeded so far with the calculations, we will see how the drawings on Plate XVII are made, from these given and calculated dimensions.

149. *Right Section.*—This is given in Fig. 60, constructed with the given dimensions. Its position on the plate is to economize space.

150. *Plan.*—In Fig. 61, ADJH is the plan of the intrados, and NPWV is the plan of the extrados, the angle of obliquity BDA being equal to 48° 30′, and DL the width of soffit on the square = 29.55 ft.

151. *Development of Intrados.*—This is shown in Fig. 62, and is obtained in the usual way as follows: AR is equal to the length of the right section AEB = 38.22 ft. The development of the face lines AD and HJ are the reverse curves AF and HG. Then AF joining the points F and A, represents the development of the heading spiral to which the heading joints of the arch are to be parallel, and to which the coursing joints are normal. Divide AF and HG into a convenient number of equal parts, preferably an odd number and a number sufficiently large that the thickness of the voussoirs be not too great; 31 were taken in this case, and the length of each one or the thickness of a voussoir is 1.501 ft., since the length of the heading spiral previously calculated was 46.535 ft. From F let fall a perpendicular on HG, which will represent the development of a coursing joint. If this line passes through one of the divisions on the heading spiral HG, we may proceed with the design of the arch without any change in the dimensions. If it does not pass through one of the points of division, the dimensions must be adjusted so as to make it do so. This may be accomplished by one of the following ways:

1st. By changing the span.

2d. By changing the width of soffit on the square.

3d. By changing the angle of obliquity; or, lastly, by a slight change in all these dimensions.

If all the dimensions of the arch are unalterably fixed the first coursing joint through F must be drawn through the nearest division on HG, in which case the heading and coursing joints will not be perpendicular to each other, and the soffits of the stones will be out of square. It will seldom occur that all the dimensions are so unalterably fixed that the slight change necessary cannot be made. When the arch is to be constructed of brick it is not necessary to make this adjustment, as the extreme variation can never exceed the thickness of a brick, or about $1\frac{1}{8}$ in. When the arch is built entirely of stone this adjustment should be made. When, as in brick arches, this adjustment is not made, the change in the angle of intrados and extrados should be calculated in order to get the correct angle of twist.* As in this case the perpendicular from F passed through a division on HG no adjustment was necessary. This was accurately ascertained from the calculations without relying on the drawing, since $GK = 22.511$, which is exactly 15 times 1.501, the width of a voussoir. The *angle of intrados* is the angle in the development made by the intersection of the coursing joints with the impost, and the *angle of extrados* is the corresponding angle made in the extradosal development—the former angle is designated by β, and the latter by ϕ.

152. *Development of the Extrados.*—As will be seen later it is not necessary to develop the extrados. In this case it was made, but is not reproduced here. It may be constructed similarly to that of the intrados. Care should be taken in fixing the position of the heading spiral, remembering that the helicoidal surfaces forming the beds of the stones are generated by lines *normal* to the axis and radiating from the axis. The heading spirals are divided into the same number of equal parts as in the intradosal development. The impost lines AH and NV are divided into the same number of equal parts as were cut off on the heading spiral of the intrados by the line FK. Then through a point on the impost, and a corresponding one on the heading spiral, a line is drawn for the direction of the coursing joints. Lines are drawn through the other points parallel to this line, and these lines will be the developments of the coursing joints of the extrados. They are at an angle of less than 90° to the heading spiral.

* See Buck's "Essay on Oblique Bridges," page 29, for method of calculation.

153. *Heading Joints.*—The coursing joints having been drawn in the developments, it remains to cut the courses up into stones by the heading joints, which are drawn parallel to the heading spiral first drawn. They are drawn through the points of division on the impost previously obtained, and so arranged as to form regular bond throughout the whole of the developments.

154. *Plan of the Intrados.*—For the sake of avoiding confusion the plan of the intrados only is given, which is obtained from the development, similarly to that in Fig. 44 of the text.

155. **The Oblique Section.**—This is shown in Fig. 63. The oblique sections of the intrados and extrados are *segments* of ellipses. These ellipses have for their semiminor axes the radii of the intrados and extrados of the arch, and for their major axes distances corresponding to AD and NP, but calculated for a semicircular arch with radii of intrados and extrados respectively equal to 16′ 3″ and 18′ 7″. These major axes will accordingly be 32.5 × cosec 48° 30′ and 37.333 × cosec 48° 30′, or respectively 43.39 and 49.85 ft. Both of the curves of the oblique section are arcs of true ellipses, and must be accurately computed, so that they may be laid out full size as required. The ordinates of points on the curves are obtained from the equations of the ellipses, which are as follows:

Equation for Intradosal Ordinates,

$$y = \frac{b}{a}\sqrt{a^2 - x^2} = \frac{16.25}{21.695}\sqrt{21.695^2 - x^2}.$$

Equation for Extradosal Ordinates,

$$y_1 = \frac{b_1}{a_1}\sqrt{a_1^2 - x_1^2} = \frac{18.583}{24.925}\sqrt{24.925^2 - x_1^2}.$$

Since in this case $a = 21.695$, $b = 16.25$, $a_1 = 24.925$, and $b_1 = 18.583$.

Values of y and y_1 should be computed for different values of x and x_1, and a table arranged similarly to the following:

Values of x and x_1.	Values of y.		Values of y_1.	
Feet.	Feet.	Inches.	Feet.	Inches.
0	16	3	18	7
1	16	$2\frac{13}{16}$	18	$6\frac{13}{16}$
2	16	$2\frac{3}{16}$	18	$6\frac{1}{4}$

The abscissas are measured from the center of the arch, and the ordinates are measured vertically from the horizontal diameter of the full semicircle.

These ordinates and abscissas are for the *semiellipses*, and accordingly for the segments of ellipses, x and x_1, need only be taken equal to 20.028 and 23.144, or one half the distances AD and NP, Fig. 61, and 6′ 3″ should be subtracted from each value of y, and 8′ 7″ from each value of y_1, for the ordinates. Another table may then be arranged which will give the values of the ordinates and abscissas to the segments of the ellipses shown in Fig. 63.

156. *Face-joints.*—The positions of the joints on the intrados are obtained from the divisions on the developed *face*-line of the intrados. Their position on the extrados might be found similarly from the development of the extrados. These joints are not straight lines, although they are usually treated as such. As the development of the extrados is not usually made, some other method of getting the position of the joints on the extrados will be used. A remarkable property of the face joints of an oblique arch was found to exist.* It was found that the chords of these joints, if produced, would all intersect below the center of the true cylinder, and that this property would still exist even though the obliquity was so great as to depress the point out of the cylinder altogether. This distance, which is CO in Fig. 63, is found from the following equation:

$$\text{CO} = \frac{s \,.\, \cot^2 \theta(\text{R} + e)}{\text{Arc AEB}},$$

or in this case

$$\text{CO} = \frac{30 \times .88473^2 \times 18.583}{38.22} = 11.417.$$

Or this distance might be found graphically, as follows: In Fig. 64 draw OG equal to the radius of the extrados = 18 ft. 7 in., and draw GH perpendicular to it, making the angle OHG equal to $\theta = 48°\ 30'$. Make the angle HGI $= \beta = 34°\ 47'$, and draw HI perpendicular to GH, intersecting GI in the point I. Then HI is equal to the distance CO in Fig. 63. This distance is

* See Buck's Essay, Chap. II.

called the *focal eccentricity*. The face joints are then drawn through the point O and through the divisions on the intrados AE′D, obtained from the development as previously explained.

As will be observed, all the stones of the arch, with the exception of the ring-stones and the skew-backs, will be of the same size, and one set of directing instruments may be used for them all. The development of the soffit face of the stones in the interior of the arch is rectangular, but those of the ring-stones are not rectangular on one side, as the developed face-line is not parallel to the heading spiral, to which the heading-joints are parallel. Each one of these stones is of varying length, and a pattern of the soffit of each is necessary. For this purpose it is necessary to find how the developed face-line may be obtained from calculations, without relying upon the drawings. Referring to Figs. 65 and 66, Plate XVIII: "Let A*a*B be the half of a semicircular arch, the obliquity of which is BDC, and suppose it is required to produce the development D*e*E by means of ordinates obtained by calculation.

"Let the arc AB be divided into a convenient number of parts and its development, BE, into the same number. Suppose a to be one of the divisions of the arc and b its corresponding division in the development, such that $\mathrm{E}b = \mathrm{A}a$.

"Also, let AC the radius = R,

$$\angle\ \mathrm{AC}a = \epsilon,$$
$$\angle\ \mathrm{CDB} = \theta,$$
$$\angle\ \mathrm{BED} = \beta.$$

Then $\mathrm{C}c = \mathrm{R} \sin \epsilon$, and $cd = \mathrm{R} \sin \epsilon \cot \theta = be$.

$\mathrm{E}b \times \tan \beta = bf$, then $be - bf = fe$.

"Thus having found a sufficient number of distances, fe, corresponding to divisions of the arc AB or to its development BE, and consequently to DE also, let DE be divided into the same number of parts as shown in Fig. 65.

"At each of the divisions draw the ordinates fe, Fig. 65, making all the angles, Dfe, each equal to the complement of BED, which is the intradosal angle being treated of, and upon these ordinates set off the distances fe, as previously calculated; then the curve D*e*E, drawn through the points thus obtained will be the development required.

"Only one half of the development is shown because the ordinates for the second half are equal to those on the first half, but applied on the contrary side of the line DE." *

It is not best to make the parts equal throughout the whole of the arc, but more should be taken at the sharpest parts of the curve. It is convenient to arrange them in several groups, each group consisting of equal parts, corresponding to groups on the development. A convenient form for the arrangement of these calculations is as follows:

1 Angles ACa or ϵ.	2 Log sin ϵ.	3 Log R cot θ sin ϵ or log *be*.	4 Nat. num. *be*.	5 Values of *bf*.	6 Ordinates *fe* or *be* − *bf*.
6° 12° etc.	9.019235	.176896	1 .503	1.181	.322

Column 1 contains the different assumed values of the arcs whose ordinates have to be found.

Column 2 contains the corresponding logarithmic sines of the angles in column 1.

Column 3. The numbers in this column are the logarithms of the lines *be*, Fig. 66, and are obtained by adding log R log cot θ to each of the numbers in column 2. In this case

$$\log R = \log 16.25 = 1.210853,$$
$$\log \cot \theta = \log \cot 48° \ 30' = 9.946808,$$
$\log R \cot \theta = 1.157661$, and this added to each of the numbers in column 2 produces the numbers in column 3.

Column 4. This column contains the natural numbers corresponding to the logarithms in column 3.

Column 5. The numbers in this column are obtained in the following easy manner: The perpendiculars *bf*, Fig. 66, divide the development BE proportionately to the divisions of the quadrant, and the lines *fg*, drawn from the points of intersection *f* and parallel to BE, will divide BD in the same ratio. Now BD, Fig. 66, is half the obliquity of the arch, which has been found before to be 26.54 (§ 148); therefore BD = 13.27 and the other values of *bf* are proportional to the respective angles in column 1, as will be evident by inspection.

*From Buck's Essay, p. 20.

Column 6 consists of the differences in columns 4 and 5, and are the values of the ordinates *fe*.

This development, to be of practical utility, should be laid down with the full dimensions.

The above method of procedure for a full-centered arch applies also to a segmental arch, the angles in column 1 will, of course, extend only up to one half the central angle AXB in Fig. 60, or in this case 67° 22′ 48″.

157. *Angles Between the Face-joints and Coursing-joints.*—The most difficult part of the cutting of the stones for an oblique arch, is to work those which form the face of the arch so accurately that they shall take their place without requiring any paring.

Having obtained the patterns of the soffits of the stones from the full-sized development, it now remains to obtain the angles between the face- and coursing-joints, there being two different angles to each face-stone, the angle on the right hand of one stone being the left-hand angle of the adjacent stone.

It is recommended that these angles be obtained at the bridge site, if possible, when no difficulty will exist. The front faces of the stones should be left in their rough state, the exact angle being obtained mechanically at the site and the faces cut just before setting. One method of obtaining the angles mechanically, by use of a bevel gauge or shifting-stock, is of interest. The stock is applied as follows: "The centers having been set, the lines of the coursing spirals were marked out upon them, and also the lines of the faces; in the plane of the face a tack was driven in the point of eccentricity before described. Augur-holes pointing towards the points of eccentricity were bored through the lagging at the points where the coursing spirals intersected the line of face; a chord was then stretched taut, passing through and connecting the two points and projecting beyond the lagging; the shifting-stock was then set to the angle formed by the chord and the coursing-spiral on the lagging, which was the angle required for that joint; the shifting stock was then clamped and the angle transferred to the stone." *

There are several different methods used for obtaining the angle by computation for use at the quarry, one of the best of

* Trans. Am. Soc. C. E., vol. XXIII. p. 167. See also Dobson's "Masonry and Stone-cutting," p. 105, for another mechanical method.

which is as follows: "Fig. 67 Plate XVIII, is a graphic representation of the angle to be computed. Fig. 67, a diagram illustrating the method. Let *on* be the half arch on the square, *ra* being the radius, R; make $rs = \text{R} \times \sin\phi$, $ry = \text{R} \cos\phi \tan\theta$, yc = radius of oscillatory circle $= \frac{\text{R}}{\sin^2\beta}$ in this case $= \frac{16.25}{.57047^2} = 49 +$.

"From the points *a* in the semicircle of the arch, corresponding to joint-points, draw lines *ar* to the center, making the angles γ, being equal divisions of the quadrantal angle. With *rs* as a radius describe the arc *sq*, and from *a* drop the perpendicular *ap;* from *a′* draw *a′a″* parallel to *ro*, and perpendicular to *a′d*.

Now, $a'd = rs \times \sin\lambda = y$; $rp = \text{R} \times \cos\lambda = x$.

$$\tan a''yn = \frac{x}{y + \text{constant } ry}."$$

The values obtained from these equations may be arranged in a table similar to the following which requires no further explanation.

λ Angle of Face-joint with Horizontal.	Log Sin λ	+ Log 10.147 or 1.004526.	Nat. Nums. *y*.	Log cos. λ.	+ Log. 16.25 or 1.210858.	Nat. Nums. *x*.	*y* + 14.884.	Nat. tan Face Angles with Vertical.	Face Angles.
4° 3′	8.848971	1.853497	.713	9.998914	1.209767	16.200	15.097	1.0736	47° 2′

"The actual face angles are deduced by subtracting the angles γ from 90° for the acute side, and adding the same angles to 90° for the obtuse side, and adding in each case the angle formed between the tangent to the oscillatory circle and its chord of the length of the stone along the coursing-joint," which might be arranged in a table as follows, "which is simply a continuation of the preceding table." *

Number of Joint.	From Table above.	Acute Angles.
1	90° − 47° 2′ + 2° 36′	45° 34′

* From Buck's Essay, p. 54, and improved upon by Crowell in Trans. Am. Soc. C. E., 1890, XXIII. 167.

We now have most of the dimensions for making the directing-instruments of all the face-stones in the arch, and also of those required for the other stones. The method of making other necessary calculations will be given as required.

158. *Directing-instruments and Method of Working a Regular Voussoir.*—While the soffit and extrados are warped surfaces the beds are *radial* warped surfaces, and usually being larger than the other faces they are worked first. These beds are portions of spiral surfaces, generated as previously described (§ 146). As the lines which generate these surfaces move uniformly, both along the axis of the arch and also from one springing-line to the other, the ratio of their motions is constant, and the spiral surfaces of all the stones will be exactly alike for equal lengths. The relation between the successive positions of the generating line depends upon the distance that the lines are apart, and this variation is called the "twist," and the twist for a given length in one part of the spiral would be the same for an equal length in any other part of the spiral. It is evident that the twist is measured by central angles, its amount at any part of the surface being a function of the radial length. And as the beds of the stones are the parts of the surfaces included between the intradosal and extradosal cylinders the amount of twist is the difference between the functions of the respective radii of the two cylinders, i. e., the difference between the intradosal and extradosal angles is the angle of twist, or wind of the bed, and this angle is called δ.

These spiral surfaces are called winding-beds, and being warped surfaces are worked by use of twisting-rules as previously described (§ 51). Although repeating some of the foregoing, the manner of procedure is as follows: Two rules, one of which has its edges parallel, and the other diverging, are placed at a determinate distance apart on that surface of the stone which is intended for the bed, and then each is sunk into a draft in the stone until their upper edges are in the same plane, when the lower edges will be in the winding surface or bed. This being done, the other parts of the beds of the stones are worked by applying a straight edge from one draft to the other, which is kept parallel to the soffit, and the superfluous parts of the stone are dressed off.

In order that no mistake be made in applying these rules, as

well as to obviate the necessity of measuring the divergence on each stone, they are connected by light iron rods, as shown in Fig. 73. These rods have fixed eyes on one end and a hook on the other. The ends with the fixed eyes are fastened to the beveled rule, and the hooks drop into eyes on the side of the other rule. The length of the rods being computed, the proper degree of divergence or radiation will be obtained. It is very important that the rules be connected, for if they are not, the workman will generally apply them parallel to each other, which will cause the wind of the bed to be greater than it should be. We must now find the radiation between the rules for the length of the rods.

Let l be the distance between the equal ends of the rule on the intrados,

$$\beta = \text{angle of intrados} = 34^\circ\ 47'$$
$$\phi = \text{angle of extrados} = 38^\circ\ 27'$$
$$\delta = \phi - \beta = \text{angle of twist} = 3^\circ\ 40'.$$

Then l_2 = distance between the rules on the extrados $= l \times \dfrac{\sec\phi\cos\delta}{\sec\beta}$ and d = difference in width of bevel rule $= l_2 \times \tan\delta$.

In this case as l was taken $= 4.322$ ft.,

$$l_2 = l \times \frac{\sec\phi\cos\delta}{\sec\beta} = 4.523,$$

and $d = l_2 \times \tan\delta = .290$ ft.

This set of rules is applicable to every stone in the arch, and as many duplicates of them may be made as desired.

Having worked one bed of the stone, the soffit is obtained from it by use of the "saddle-mould," Fig. 68, which is made as follows: Prepare two moulds or arch squares as shown in Fig. 72, where AC is the radius of the cylinder and DB is the thickness or depth of voussoirs. These arch squares are prepared in the usual manner, the stock AB being made to fit the curve of the soffit on the right section, and should be preferably as long as the stones are to be wide, or longer. Make BD equal to the depth of the voussoirs, with both edges radiated to the center. These two moulds are turned back to back, and framed together as shown in perspective in Fig. 68, and so placed that the angle ACB shall be equal to the complement of the angle of intrados. Having done this the edges of the blades BD and CE will exactly

coincide with the spiral bed of the stone, which has already been worked by use of the twisting-rules. The stone is then placed with its soffit face uppermost, the saddle-mould is inverted and applied with its blade in contact with the worked bed, while the curved strip BC lies on the soffit of the bed DF, as shown in Fig. 69. Then draw a line on the stone along the stock AC, and this line will be at right angles to the axis of the cylinder. Another line is drawn along the side AB, which will be parallel to the axis of the cylinder. Remove the saddle and sink drafts in the soffit on the line CA to fit the curve of the stock, and also on AB to fit the side AB, this latter line being perfectly straight as it is an element of the cylinder. When the drafts are sunk to the proper depth, the saddle-mould, on being reapplied with its blades to the worked bed, and the diagonal strip to the arris of the soffit, the stock CA and the side AB will be exactly in contact in every part at the same time.

Then two segmental pieces, Fig. 70, which are similar to CA, Fig. 69, in length and curvature, are applied one to the draft AC and the other upon a line GH which is parallel and at a convenient distance from AC. The centers of the segments must be kept on the line IK, drawn parallel to AB. The second segment is sunk in a draft until its edge is out of wind with the upper edge of the one on AC, and the superfluous parts of the stone are dressed off, until a straight-edge applied parallel to AB coincides with the soffit in every part.

Then the other arris, LM, of the soffit is gauged and knocked off parallel to FD, and the bed on LM is obtained from the soffit by turning the saddle-mould about and reversing the former procedure. The ends of all the stones except the ring-stones, are worked square on the soffit. The joints on MD and LF, or the heading-joints, are worked to fit the radiation of the blades of the saddle-mould. The saddle-mould is applicable to every stone in the arch.

In the right arch the soffit of a stone is worked by use of the arch square, which is moved along at right angles to the axis. In the oblique arch the courses, instead of being parallel to the axis, extend crosswise of the arch, and the arch square, if used, must be applied at right angles to the axis. The saddle-mould is only a convenient tool for accomplishing this.

Face-stones.—The beds are worked by use of the twisting-rules and saddle-mould, as in the regular stones. The patterns of the soffits of the stones are obtained from the full-sized development of the intrados. The proper face-angles are obtained from the soffit face by use of bevels prepared according to the respective computed face-angles.

This arch is said to skew to the left, according to the supposition that if you stand in the axis of the cylinder and look through the arch the acute quoin of the abutment will be on your left hand.

159. *The Impost and Saw-teeth Skew-backs.*—The impost on which the arch rests is divided into a number of triangular checks, which project into the curve of the arch sufficiently to intercept one width of voussoir. The patterns of the intrados and extrados are flexible triangular strips, that of the former being shown in Fig. 71, the dimensions of which are found as follows: The width of a course of the soffit $= 1.501$, and the angle of intrados is $34° 47'$, therefore the length of the hypothenuse of the triangle $= 1.501 \times \sec 34° 47' = 2.631$. Or it equals the length of the impost $39.46 \div$ the number of checks 15, which makes each one $= 2.631$. A similar template may be made for the extrados. The soffit face may be worked by use of an arch square. The difference in the angles of the two templates will produce the proper degree of wind in the bed and cross-joint. If these stones were cut without being made a *part* of the course of masonry below them, they would crack off at the points B and C, and there would be a great tendency to move over the impost. They are accordingly made a part of this course, and should extend squarely back into the rest of the masonry.

160. *Locking the Ring-stones.*—In an arch, the obliquity of which is great, the lowermost ring-stones on the acute side have a tendency to slide out. In the Oakley Arch this was overcome by two devices, a description of which is given in the Trans. Am. Soc. C. E., vol. XXIII. p. 172.

161. **Erection.**—As soon as the abutments have been carried up to the springing-lines, and the impost-stones placed, the centering should be set in its place, with the ribs parallel to the face of the arch. The lagging should be fastened down securely, projecting a few inches beyond the faces of the arch, their upper

faces being planed perfectly true to coincide with the curve of the soffit.

The lines of the coursing- and heading-joints must now be marked upon the lagging to assist the workmen in setting the stones. This is done as follows, referring to Fig. 61: Draw the face-lines AD and HJ, which will be straight in plan. Bisect them and draw a line between the center-points. Divide this line into the same number of parts as the impost line is divided. Prepare a long, thin, flexible, straight-edge. If the bridge is of not too large dimensions, so that the straight-edge may extend from the impost to the crown (or half the length of the heading spiral), apply the straight-edge from the first division on the impost to the first on the crown, as from A′ to E″, Fig. 61, and draw a line which will be the heading spiral. On the straight-edge mark off divisions for the width of voussoirs, and transfer these points, *a*, *b*, *c*, etc., to the heading spiral already drawn. Draw other heading spirals similarly, transferring the divisions on the straight-edge to them, being careful that the center line at the crown passes through the *center* of a division in each case. The coursing spirals are then drawn through the several points.

When the arch is constructed of brick it is not necessary to draw the heading spirals.

A suitable system of numbering the stones on the drawings and on the laggings should be adopted, so that no delay shall occur in setting the stones.

162. Voussoir in Plaster.—Fig. 34 in the text is a regular voussoir of this arch cut from plaster. The voussoir is made to a scale of one inch to the foot. The dimensions of the patterns for the voussoir are those calculated in previous paragraphs. These dimensions are as follows: The rectangular pattern of the intrados is 4.322 ft. × 1.501 ft.; the pattern of the extrados is 4.53 ft. × 1.65 ft.; the thickness of the voussoir is 2 ft. 4 in.; one end of the twist rule is .29 ft. wider than its other end and the width of the parallel rule.

The rules are fastened together at the correct distance apart by wires, and small nails, taking the place of the iron rods used in actual work. The voussoir is cut exactly in the manner outlined previously, except an arch square applied correctly by use of

a bevel set to the angle which is the complement of the angle of intrados, takes the place of the saddle-mould.

ART. 3. THE COW'S-HORN METHOD. THE LOGARITHMIC METHOD.

163. Corne de Vache, or Cow's-Horn Method.—The soffit of the arch is a warped surface, from the appearance of which comes the name of the arch. This warped surface is generated by a straight line moving upon two equal and parallel semiellipses (semicircles as a special case), and always touching a straight line. In Fig. 46, $AB - A'B'$, and $A_1B_1 - A_1'B_1'$ are the two semiellipses, in this case semicircles, and they are the heads of the arch. The semicircle $N'M'P'$ is the extrados of the arch. The plan of the arch is NPP_1N_1. The right line directrix is $OO_1 - O'$, which is perpendicular to the traces of the heads, and passes through the point of symmetry of the figure. A line, as $AA_1 - A'A_1'$, moving

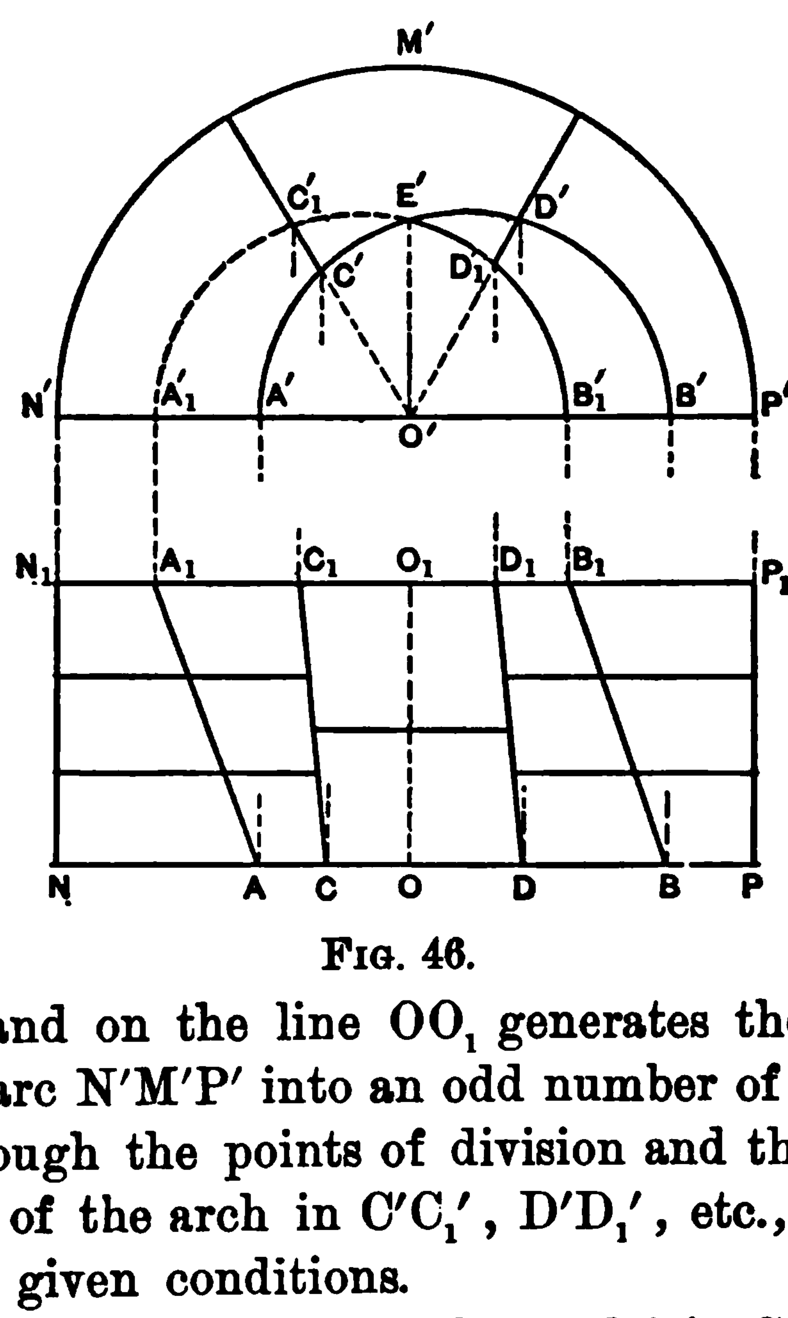


FIG. 46.

on the circles and on the line OO_1 generates the intrados of the arch. Divide arc $N'M'P'$ into an odd number of equal parts, and pass planes through the points of division and the axis OO_1, cutting the heads of the arch in $C'C_1'$, $D'D_1'$, etc., and these joints will satisfy the given conditions.

Project C' into C, and C_1' into C_1, and join CC_1, which will be one of the coursing-joints of the arch. This coursing-joint is an element of the warped surface forming the soffit of the arch.

The heading-joints are parallel to the faces of the arch. The available height of the passage is O′E′, and as the angle of skew increases this height diminishes, until finally the arch becomes two cones and the passage becomes closed.

For a more complete description of this form of arch consult No. 17 of Van Nostrand's Science Series, by Prof. E. W. Hyde.

164. The Logarithmic Method.—This method is so called because Naperian logarithms are used in its calculation. The soffit of the arch is cylindrical, as in the helicoidal method.

In this method the soffit coursing-joints are perpendicular to the plane of the arch face wherever they come in contact with it. The heading-joints on the soffit are elliptical curves parallel to the arch faces, and are therefore normal to the coursing-joints at their intersections. These joints being normal to each other will also be normal to each other in the development of the soffit as shown in Fig. 47.

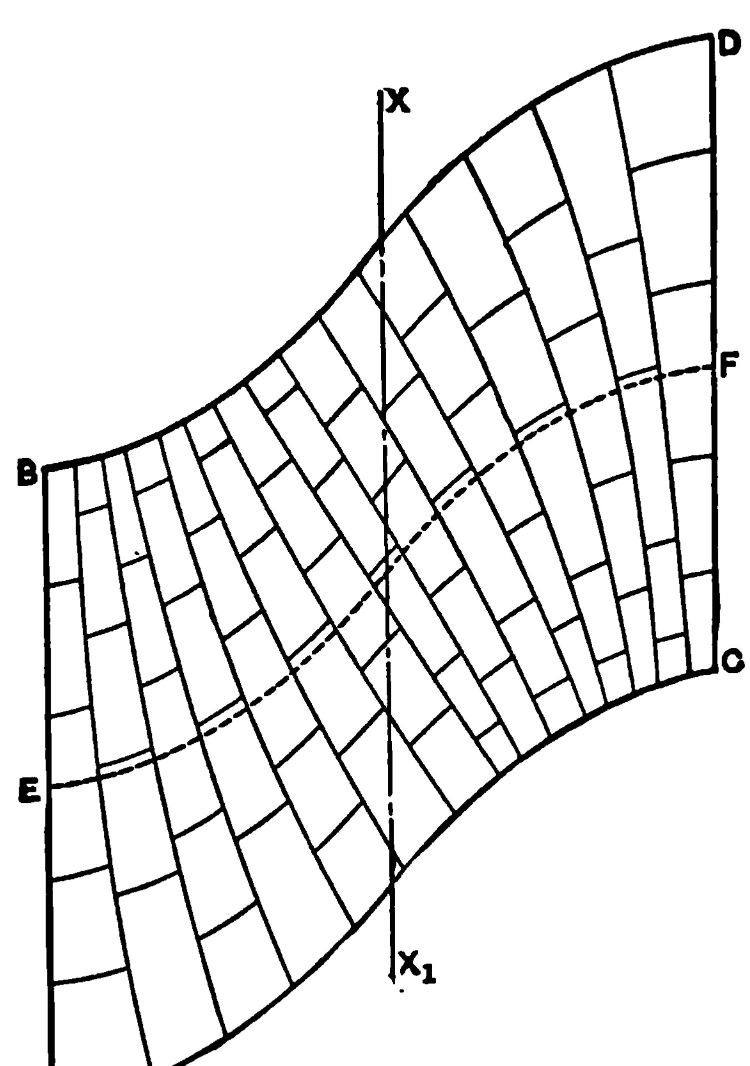


FIG. 47.

The widths of the courses are fixed on the curve EF midway between the curves of the developed faces of the arch. The developed heading-joints are drawn parallel to the curve AC. The coursing-joints are at right angles to the heading-joints.

The coursing-beds in this method are generated by a radial line normal to and moving along the axis of the arch, and touching the intradosal coursing-joints. The logarithmic and helicoidal methods are accordingly quite similar in construction. (§ 146.) The courses in the logarithmic method vary in thickness across the soffit of the arch, no two stones in the same course being the same, although two courses beginning at opposite ends of the arch at the same height above the springing lines are exactly alike. On account of this divergence of the courses, a separate set of templates must be used for each stone, with the exception just noted. Brick cannot be used in this method.

For descriptions of the logarithmic method see numbers 17 and 87 of Van Nostrand's Science Series, by Prof. Hyde and J. L. Culley, from the latter of which Fig. 47 was taken.

Art. 4. Bibliography of the Oblique Arch.

165. Some of the works which have been published relating to the construction of oblique arches are given below. The list is not complete.

Peter Nicholson. 1828. Practical Treatise on Stone-cutting.

Charles Fox. 1838. Pamphlet, On the Construction of Skew-arches.

John Watson Buck. 1839. A Practical and Theoretical Essay on Oblique Bridges. Second edition, with the addition of description to diagrams for facilitating the construction of oblique bridges, by W. H. Barlow. 1857. John Weale, London.

Peter Nicholson. 1839. Treatise on the Oblique Arch.

John Hart. 1837. Practical Treatise on the Construction of Oblique Arches.

C. A. F. Leroy. Traité de Stéréotomie. Plates and text. 1845. Praly, Paris, 1853; Graeff, Paris, 1853; Adhemar, Paris, 1861.

Francis Bashforth, 1855. A Practical Treatise on the Construction of Oblique Bridges.

Edward Dobson. The Rudiments of Masonry and Stone-cutting. 5th Edition, 1869. Weale's Series, London.

A graphic method of setting out the face-angles of skew-bridge

voussoirs. A method devised by M. D. Connery. *Builder*, London, June 18, 1898.

Wm. Donaldson. Oblique Arches. Plates.

George J. Bell. Oblique or Skew Arches. A Practical Treatise on Segmental and Elliptical.

The above are all English or foreign works. Among American books and articles on the subject are the following:

S. E. Warren. 1875. Stereotomy and Stone-cutting. John Wiley & Sons, New York.

E. W. Hyde. Skew Arches. Advantages and disadvantages of different methods of construction. Van Nostrand's Magazine, Feb.-April, 1875. The helicoidal, logarithmic, and cow's-horn methods, with a comparison of the three methods. Issued as No. 15 of Van Nostrand's Science Series.

J. L. Culley. Helicoidal Oblique Arches. A simple exposition of the theory and method of designing the templets and twist rules. Van Nostrand's Magazine, April and May, 1886. Issued as No. 87 of the Science Series. Also contains a brief description of logarithmic and ribbed oblique arches.

The following are articles upon the design and construction of oblique arches with spiral courses. Examples of false and ribbed skew-arches are given in the next two articles.

1. Description of a Skew Arch built at Harrisburg, Pa. Van Nostrand's Eng. Mag., 1876, XIV. 361–364.

2. St. Paul, Minn., Seventh Street Improvement. Plan, elevation, description, cost, etc. Helicoidal method used. *Eng. News*, 1885, XIV. 245. Also more complete article on the same in Jour. Assoc. Eng. Soc., July, 1886, v. 317.

3. The "Domino" Arch. On the Pennsylvania and Schuylkill Valley Railroad, carrying a double-track railroad embankment over a city street in the outskirts of Philadelphia. This has no quoin-stones, the face being of brick, rubbed to the correct shape. The skew-back is "saw-tooth," and there are original features. 50 ft. span, 12 ft. rise. Proc. Eng'r's Club of Philadelphia, 1886, v. 3.

4. Construction of a Skew Arch. J. L. Culley. Proc. Eng. Club of Philadelphia, 1886, v. 212.

5. Oakley Arch. On the Designing and Erection of the Oakley Arch. A full-centered construction of extreme skew, to

carry a railway embankment over another double-track railway. J. Foster Crowell. Trans. Am. Soc. C. E., 1890, XXIII. 155.

Among other arches built with spiral courses, besides those described in the above articles, are:

The "Reading Arch Culvert," on the Cincinnati and Richmond Railroad, near Reading, Ohio. This, though only of small diameter, 10 or 12 feet, is a beautiful example of a skew with stone quoins and saw-teeth skew-backs.

The Sixth Street Arch, Reading, Pa., taken as an example (§§ 147–162), and "a skew-bridge on the Lebanon Valley Railway, are given in Osborne's "Select Plans for Engineering Structures, vol. I."

The William Street Arches in the New York approach to the Brooklyn Bridge are true skews, 60 ft. span, low rise, granite quoins and saw-teeth, and are very admirable examples.

ART. 5. THE "FALSE" SKEW-ARCH.

PLATE XIX.—THE NEW STREET ARCH OF THE FITCHBURG RAILROAD, AT FITCHBURG, MASS.

166. This arch carries New St. over the Nashua River. There are two spans of 38 feet each and two spans of 14 feet each. The angle of skew is 45°, and there is only 30 feet of the total length of 70 feet of the abutments squarely opposite. The construction of this arch was considered a very bold piece of engineering work.

Plate XIX is a most complete working drawing for the arch, and is an almost exact reproduction of the 28″ × 40″ sheet according to which the arch was built. The details are so carefully worked out that the student only needs to study the drawing to fully understand it. The notes attached are unusually complete.

All dimension stones are of first-class masonry. The abutments below skew-back are built of second-class masonry, while the retaining-walls and backing of the arch are made of third-class masonry. Note the method of distinguishing the different classes of masonry in the sections of the retaining-wall.

The arch is three-centered, the radii differing by only a small amount. The right section gives the elevations of the several courses, the radii and central angles of the arcs, etc.

The elevation of the arch at right angles to the axis gives in a complete and simple way the necessary dimensions for the face-stones of the arch. The dimensions on the soffit are the widths of the voussoirs at right angles to the axis. As this elevation is taken in a plane at right angles with the axis, and as the thickness of the voussoirs is in this plane, it is evident that if measurements are given from such a plane to the corners of each face-stone, the face of the arch will have the desired skew. Thus in the plate the figures given at the corner of each ring-stone indicate the amount that corner projects beyond the shortest edge of said stone, which corner is marked "O."

The following are additional examples of "false" skew-arches.

167. Literature.—1. Colorado Street, St. Paul. Coursing-voussoirs parallel to lines of skew-backs, instead of in helices. *Eng. and Building Record*, Nov. 23, 1889.

2. False Skew-arches. A communication relating to the practice of building false skew-arches, by an engineer who has constructed a number of them. *Eng. News*, 1887, p. 201.

3. Kankakee, Ill. Two stone arches. Segmental, with 20′ 6″ span and 3′ 6″ rise. Angle of skew 30°. *Eng. News*, 1899, vol. XLI. p. 197.

4. Stone Arch Bridges on the Fitchburg Railroad. Description of the New Street Arch and the Putnam Street Arch over the Nashua River, at Fitchburg, Mass. Angle of skew of the former 45°, and that of the latter 25°. Jour. Assoc. Eng. Soc., July 1901, vol. XXVII. 1.

Among other examples of "false" skew-arches may be noted the following: The "Montgomery Road" Arch, carrying a city street over the Cincinnati and Richmond Railroad in the outskirts of Cincinnati. Skew-angle quite light. Span 24 feet, semicircular. Limestone face-stones and skew-back walls with brick barrel.

There are numerous examples of false skew-arches on the Pennsylvania and Schuylkill Valley Railroad, on the Boston and Maine Railroad, and on several other roads. They are quite generally used when the angle of skew is small enough to warrant it. The above list is not complete, but is merely a suggestion to the student as to where he may find examples of this form of arch.

ART. 6. THE SKEW-ARCH WITH RIBS.

PLATE XX.—TRENTON BRIDGE, PENNSYLVANIA RAILROAD.*

168. This is a good example of a skew-arch with ribs. The example taken is the arch which crosses the Delaware River between Trenton and Morrisville, N. J., on the Pennsylvania Railroad. It consists of eighteen skew-arches of 60 ft. span in the clear. The arches are carried on fifteen piers, 8 ft. thick at the springing lines, and two abutment-piers, 22 ft. thick at the springing lines, which divide the bridge into three sections of six arches each. These abutment-piers are similar to the main piers, only they have greater dimensions, and have a longitudinal extension of the coping at the down-stream end which serves as a refuge for workmen. The bridge is composed entirely of stone masonry, and four tracks pass over it. The arches are segmental, the span being 60 ft., the rise 12 ft., and the radius 43 ft. 6 in.

Each arch is composed of twelve ribs or small right arches, which project beyond each other in opposite directions on the two sides, thus forming the proper skew. The angle of skew is 18° 30′. The ribs are 52 inches wide, and are fastened together at points along the extrados by wrought-iron U clamps. Some of the details of the construction are shown in the plate.

169. Some of the main objections to the use of this form of arch are the following: 1. That it is wasteful of material on account of the ribs. 2. That it is very ugly in appearance on account of the soffit not being a smooth surface except at the crown. 3. It is an obstruction to the waterway on account of eddies forming about the ribs. This objection is only of consequence when the elevation of the water is above the springing lines, in which case it is a very serious one, especially where the stream is liable to sudden freshets. 4. That there is no bond between the several ribs, except by the use of iron clamps. 5. When properly bonded together by the use of clamps, it is a question whether any of the other methods of construction would not be cheaper.

The following are examples of this form of arch.

170. Literature.—1. Steele. On Skew Bridges, and on the Construction of Falls Skew Bridge over the Schuylkill River near Philadelphia. Trans. Am. Soc. C. E., 1872, I. 209.

* *Eng. News*, 1902, XLVII. 96.

2. The North Avenue Masonry Arch Bridge, Baltimore, Md. Three skew-arches of 30 ft. span and 26 ft. rise, each arch consisting of twenty-five ribs 4 ft. wide, with offsets of 28 ft. at the springing line. Angle of skew = 35°. *Eng. News*, 1893, xxx. 7.

3. Masonry Arch Bridges at Trenton and New Brunswick, N. J., on the Pennsylvania Railroad. *Eng. News*, 1902, XLVII. 86.

4. Ribbed Arch Bridges on the Lebanon Valley Railroad at Fourth and Fifth streets, Reading, Pa. Designs in Osborne's "Select Plans of Engineering Structures," vol. I.

The Pennsylvania Railroad has a number of ribbed brick and stone arches on the New York, Philadelphia, Middle, and Pittsburg divisions. This road uses the ribbed form quite generally for its skew-arches.

CHAPTER VI.

OTHER PROBLEMS.

ART. 1. THE RECESSED MARSEILLES GATE.

PLATE XXI.

171. **Problem.**—Let the line BC, Fig. 83, be the vertical trace of the back of a wall, and *ad* that of the face, also vertical. Through this wall is an arched passageway, with gates placed in a recess in the wall between the face and back. The gate is composed of two leaves, and when thrown back they take the position A_1a and D_1d by revolving about the vertical axis projected in A_1 and D_1. The problem consists in arranging the surface of the recess under which the leaves, swing in opening or closing: 1st, that it shall offer no obstruction to the swinging of the leaves; 2d, that it shall be one easily constructed; and 3d, that it shall present a pleasing effect architecturally.

172. **Projections.**—B_1BCC_1, Fig 83, is the plan of the passageway whose top is $B'F'C'$. The top of the gate when closed is a semicircle with diameter $A'D'$, the plan of which is A_1ADD_1. The doors when open rest against the vertical side planes whose traces are A_1a and D_1d, and when closed fold against the surface between the semicircles projected vertically in $A'g'D'$ and $B'G'C'$.

For the pleasing effect desired it will be best to take A_1a and D_1d not less than A_1O, half the width of the gate. Also, the front top edge $ad - y'o'k'$ should be arched, the height $G'o'$ being equal to or greater than one half OO_1. The edges of the recess projected horizontally in a and d are found vertically in $a'y'$ and $d'k'$. Take $a'y' = d'k'$ greater than $O'g'$ in order that the leaves of the gate may fold back against $D_1d - D'k'd'$, and $A_1a - A'y'a'$. Through the three points y', o', and k' pass a circular arc, the center of which is O_2.

Then let the circular arc $y'o'k'$, which is the vertical projection of the front face of the recess or embrasure, $A'g'D'$, the vertical projection of the back face of the recess, and $OO_1 - O'$, the axis of the arch, be the three given directrices of a warped surface generated by the motion of a straight line upon them. The straight line moves so that it always touches the two curves and cuts the axis. The warped surface generated covers the upper part of the top of the recess. The projections of the extreme positions of the elements of this surface will be $dX - k'j'o'$ and $aX - y'l'o'$. It remains to form the surface $j'k'd'D'$ and its symmetrical $l'y'a'A'$. To form this we take the two directrices $OO_1 - O'$ and $A'g'D'$ in common with the preceding warped surface, but replace the directrix $y'o'k'$ by a new directrix, a curve $D'm'k'$, through D' and k', so formed as not to interfere with the opening of the gate. Let us now determine the nature of this new third directrix.

Revolve D_1d around the point D_1 until it becomes parallel to BC. The point d''' is the vertical projection of d''. Then with d''' as a center and a radius equal to $d'''D'$ describe a one-quarter circumference $D'g''$. This will be the projection of the leaf on the vertical plane OD_1. In order that the leaves may swing without interference, it is necessary that the arc of the recess be above the arc $D'g''$. This arc is formed by the portion $D'm_1'$ of $D'g''$, and by the arc of the circle $m_1'd''''$. The position of the point m_1' is found as follows: through j' a line is drawn parallel to $T'k'$ ($T'k'$ being a tangent of the arc $y'o'k'$) to meet the vertical line through D' in i'. Draw $i'd''''$ and on $d''''H$, the perpendicular to $d''''i'$, lay off $d''''H = d'd'''$. Join H and d''', and at its middle point K erect a perpendicular meeting $d''''H$ produced in Z (not shown). With Z as a center and radius equal to Zm_1', describe an arc passing through m_1' and d'''''. Revolving the arc $D'm_1'd''''$ back, it takes the position $D'm'k'$.

Now let us return to the three conditions (§ 171) to be met. The second is satisfied by taking warped surfaces to form the top surface. The third, namely, that the cover shall present a pleasing effect architecturally, is obviously fulfilled if the warped surfaces are tangent to each other along their extreme elements, thus appearing as a continuous surface. Let us see if the warped surfaces are tangent to each other along their common elements

dX $-$ k'O$'$ and aX $-$ y'O$'$, and at the same time see the reasons for the above constructions.

The two warped surfaces having two directrices in common, i.e., the axis of the arch, and the semicircle projected vertically in A$'g'$D$'$, will have two tangent planes common to the surfaces along each of the extreme elements k'O$'$ and y'O$'$. Now construct a tangent plane to the warped surfaces at the point k' by drawing a tangent to the curve projected in D$'k'$ at this point, and through this tangent and the element projected in k'O$'$ passing a plane. The element k'O$'$ pierces the vertical plane of which A_1D_1 is the trace at $j - j'$, and the tangent to the curve k'D$'$ at k' intersects the vertical line D$'$D$''$ at i'. Then joining j' and i', the line $j'i'$ will be the projection of the trace of the tangent plane on the vertical plane A_1D_1, and its trace on the vertical plane ad is T$'k'$ parallel to $j'i'$. A curve passing through k' and D$'$ and tangent to a line through k' tangent to the arc K$'m'$ (shown in revolved position $d''''m'_1$), if taken as the third directrix of the second warped surface, the two surfaces will be tangent, as they have a third common tangent plane at the point k'. It is now necessary to find out if the first or most important condition is fulfilled.

173. **Test for Interference.**—Having constructed the warped surfaces with the arbitrary conditions, it is necessary to ascertain whether the surface generated by the top of the gate in opening interferes with them. It will be observed that the surface generated by the top of the left-hand gate, for example, is a portion of a torus, formed by the revolution of the quarter of a circle with radius O$'$D$'$ around the vertical line through A$'$ as an axis. This surface should not intersect the warped surfaces within the side planes, as A_1a and D_1d. The intersection of the two surfaces is found in the usual manner, as follows: The line Y$'s'$ is the vertical trace of a plane cutting both the torus described by the gate, and the top surface of the recess. This plane will cut the torus in a horizontal circle projected in Ys, and from the warped surface of the recess a curve sY_1Y, found by projecting s', Y_1', and Y$'$ upon the horizontal projections of the elements which contain them. When this circle cuts the other curve at a point without A_1a no interference exists for the particular point Y $-$ Y$'$ of the gate. When, however, the two curves intersect within A_1a inter-

ference exists, and the difficulty may be remedied by one or more of the following means:

1st. Increase the radius of the arc $y'o'k'$.

2d. Raise the point o' without increasing the radius of the arc.

3d. Decrease the radius of the gate-top slightly.

174. Directing Instruments.—Having found the projections of the top surface of the recess, we will now find the patterns of all the developable surfaces of the most irregular voussoir, that included between the radial joints M′P′ and N′V′. These are: the rectangular patterns of the top face, of length aa_1 and width P′U′; and of the vertical side on U′V′ of length aa_1 and width U′V′; the pattern of the back face is M′P′U′V′N′, and that of the front face is k'W′P′U′V′t'.

The true lengths of the radial joints M′P′ and N′V′ and the patterns of the faces back of them are found as follows: Taking M′P′ as an example, revolve M′P′ around M′ until parallel to **H**. The points will come to those shown on the plate, and through these points lines are drawn parallel to M′O′ intersecting the ground-line A′D′. From these last points lines are drawn parallel to OX — O′, the axis, to meet lines which are the traces of planes in which the respective points are situated. Joining the successive points gives the figure LM′$h'h_1'$W′P′I, which is the required pattern of the joint M′P′. In like manner the figure LN′$n'n_1'p't'$V′I, was constructed, which is the pattern of the joint N′t'. We might also make as many bevels for the diedral angles as we desire, such as W′P′U′, P′U′V′, etc.

175. Stone-cutting.—Choose a block of stone the dimensions of which are such that M′P′U′V′N′ may be inscribed within its end, and its length equal to aa_1. Form the plane top of the stone by use of its pattern, previously described, and then from this, by use of the square and from their respective patterns, work the vertical plane surface of the two ends and the one on U′V′. Then from the back surface work the radial beds on M′P′ and N′V′ by use of their patterns and bevels. The cylindrical portions between M′N′, etc., may now be worked.

The warped portion of the stone may then be worked, as we have all the edges, by use of the straight-edge, held at the position of several of the intermediate elements of the surface, found by transferring their extremities from the drawing to the stone.

Note.—If the distance D_1d is less than OD_1, the outer edge of the gate will fall without d when the gate is open. In this case a simple curve may replace the compound curve $D'k'$.

176. Montpellier Recessed Gate.—This differs from the Marseilles gate only by there being a right line, as $y'k'$, instead of the arc $y'o'k'$.

ART. 2. THE HEMISPHERICAL DOME.

PLATE XXII.

177. If the right section of an arch revolves around a vertical through the keystone, it will generate a dome. If the right section is a semicircle, the dome will be hemispherical.

178. Problem.—To construct a hemispherical dome.

179. Projections.—B′S′C′, Fig. 85, is the right section of the dome taken on the center line AD. The intrados is generated by B′S′C′ revolving about the vertical axis O′S′ — O. The extrados is generated by A′I′K′L′D′ revolving about the same axis. The intrados is divided into seven equal parts, and the points of division B′, E′, F′, etc., are joined to the center O′, giving the joints E′H′, F′ G′, etc., which are normal to the intrados. The joints revolving about the vertical axis O′S′—O generate portions of cones of which the center of the dome O′ is the apex. Project H′E′ into HE, F′G′ into FG, etc.; the points H, E, F, G, etc., revolved about the axis will describe circles which are the joints of the intrados and extrados. Divide the courses formed into blocks of suitable dimensions by joints of right section or vertical planes through the axis. Let HF and H_1F_1 be the projections of two joints of right section. HH_1F_1F will be the plan of the voussoir between these two joints. H′E′E″H″ is the vertical projection of the lower conical joint, and G′F′F″G″ is the vertical projection of the upper one. E′F′F″E″ is the vertical projection of the face of the stone on the soffit. The joints of right section of adjacent courses should break joint.

180. The Directing Instruments and Stone-cutting.—Select a block of stone such that E′F′G′H′ may be inscribed in its end, the length of which is equal to the chord HH_1. Construct a pattern of the soffit face E′E″F′F″ considered as a plane, as follows: The points E′, E″, F′, and F″ are the projections of the angular points of the voussoir on the intrados, and lie on the small circle of

the dome passing through the points of which these are the projections. The chords joining the two upper points, F′ and F″ and the two lower ones, E′ and E″, are shown in their true lengths in FF_1 and EE_1, and the true lengths of EF and E_1F_1 are shown by E′F′ in vertical projection. Fig. 86 is the pattern of the soffit face considered as a plane constructed from these dimensions. Work this soffit face as a plane.

Then by use of a bevel set to an angle E_1EH in Fig. 85, and the pattern E′F′G′H′, work the two faces EH – E′F′G′H′ and E_1H_1 – E″F″G″H″. Then on the face E′F′G′H′ draw a line from the point F′ making an angle with G′F′ as given in the vertical projection by the angle between G′F′ and a line through F′ parallel to A′D′. On this line apply an arch square having the curved arm cut to the radius of the small circle through F′ and F″, that is, with a radius equal to the perpendicular distance from F′ to S′O′, and work a draft on the line F′F″. Work the draft on E′E″ similarly by use of an arch square with radius equal to the perpendicular from E′ to S′O′. Then, with a templet cut to fit a circle with radius equal to the radius of the intrados of the arch, work the soffit face E′E″F″F′. Finally work the conical surfaces F′F″G″G′ and E′E″H″H′ from the soffit face by use of an arch square with radius equal to the radius of the intrados. The extradosal surface may be worked by use of a template cut to the radius of the extrados of the arch.

181. Variations.—The variations of this problem are the following:

1. The extrados may not be worked to a curved surface, the right section of the voussoirs being completed by vertical and horizontal lines as in previous problems.

2. The right section may be elliptic. For a description of this case see Leroy's "Traité de Stéréotomie" or H. Echenoz's "Coupe de Pierres."

Art. 3. Stairs.

182. Stairs in general may be divided into two principal classes:

1st. *Straight stairs*, in which both the height, or rise, and the width, or tread, are uniform for all the steps.

2d. *Winding stairs*, in which the rise is uniform, but the tread varies at different points on each step.

Winding stairs may be divided into two classes: (1) those in which the edges radiate from a single vertical axis, and (2) those in which the edges do not radiate from a single vertical axis.

The line that any one would naturally take in going up or down the stairs is called the *line of passage,* and is a certain distance from the hand-rail. In the first form of winding stairs the line of passage is a circular helix, and the tread is uniform on an ascending line at any given distance from the axis. In the other form the horizontal projection of the line of passage is not a circle, but some other form of curve.

If this curve represents the horizontal trace of a vertical cylinder on which a point moves with uniform motion, both horizontally and vertically, it will generate a helix more general than the usual one. The plan of the helix not being a circle, the horizontal projections of the successive positions of the line normal to it will not intersect in a common point; but when the positions of the line are taken indefinitely near, their intersections become continuous and form a curve to which the lines are tangent. The line of passage and this curve will have the relation of involute and evolute to each other.

THE GEOMETRICAL STAIRWAY.

PLATE XXII.

183. Projections.—Let FGJI, Fig. 87, be the base of a vertical wall along which we wish to build a flight of stone steps. For our purpose let us consider F*ab*G the lower landing, and that we have three steps connecting to a higher floor. Let the line of passage ACE be an arc of an ellipse, and the tread of the steps taken as 12 inches is laid off on ACE, giving the points B, C, D, and E. Through these points normals to the ellipse are drawn which will be the edges of the steps. The steps are built into the wall and are limited on the inner side by the curve *bc′e* at a distance of 18 inches from ACE measured on the normal joints. This curve is called the *well* of the stairs, and is the base of a vertical cylinder which limits the ends of the steps. The under-surface of the steps is a helicoidal surface generated by a line moving upon and normal to the helix, whose projection is BCE, and parallel to **H**. Each step extends under the one above it, as shown

in Bh, Cl, etc., or in the development in Fig. 88. Normals to BCE at the points h, l, etc., will be the edges of the steps.

The surfaces shown in development by h_2g_1, l_2k_1, etc., should rightly be hyperbolic paraboloids, but it is sufficiently approximate to make them normal to the lower surface at points on BCE. These points are taken at h, l, etc. on the helix BCE, because in development the helix only will develop into a straight line. Now to complete the plan of the steps it will be necessary to find the projections of the upper edges of the normal joints, to obtain which we must make a development.

Development.—Make B_2E_3, Fig. 88, = BE, Fig. 87, and E_3E_1 equal to the difference in elevation of the landing FabR and the upper floor. Then B_1E_1 will be the development of the helix *over* BE, which cuts the front edges of the steps. There being three steps, divide B_1E_1 into three equal parts, and through the points of division B_1, C_1, and D_1, draw the horizontal lines B_1C_2, C_1D_2, etc., to intersect verticals drawn through the points C_1, D_1, and E_1. Then B_1C_2, C_1D_2, etc., are equal to BC, CD, etc., and are the treads of the steps. Each step extends under the one just above it, say for six or seven inches, equal to B_2h_1, C_2l_1, etc., in development. Take h_1h_2, l_1l_2, etc., equal to one half the rise of a step and l_2h_2 parallel to B_1E_1 will be the development of the helix projected in BE.

At the points h_2, l_2, etc., draw the normals h_2g_1, l_2k_1, etc., to B_1E_1, which are lines of the planes normal to the helicoid at h, l, etc. These points are then found in plan by making gh, kl, etc., $= g_1h_1 = l_1k_1$, etc., and the lines through the points g, k, etc., parallel to hh', ll', etc., will be the horizontal projections of the top edges of the normal planes.

184. The Directing Instruments.—Take one step for an example. The pattern of the top is KRbk'. The pattern of the wall end of the step is K′R′R″G′H′S‴L′, found by projecting the outer end LR onto a parallel plane. The vertical distances of the several points are obtained from the development. Note that C_2C_3 in the development is greater than B_1B_2, and accordingly H′L′ is not a straight line.

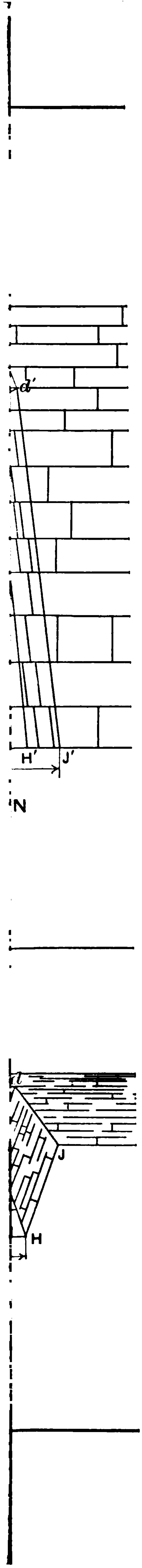
To obtain the pattern of the inner end of the step the portion of the cylinder of the well, bl', must be developed, and the cor-

responding points set off on it, the heights being taken from the development. The pattern of this end is $k'b'b''g'h'l'$.

The normal joint bevel shown at T_1 in the development will also be of assistance in cutting the stone.

185. Stone-cutting.—Choose a block of suitable dimensions, and having brought the top surface to a plane, mark the form of the top face by use of the pattern $KRbk'$. By use of the square work the end-faces and rises square with the top face, obtaining their form with the corresponding patterns. The normal joints are worked by use of the normal bevel T_1. The helicoidal under-surface is worked by use of the straight-edge applied on points determined from the drawing where elements would meet LR and bk'.

186. Variations.—Notice that the curve determined by the intersections of the normals to the helix have the relation of evolute and involute to each other. Therefore stairs may be constructed in which either curve is assumed.


d'
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J'
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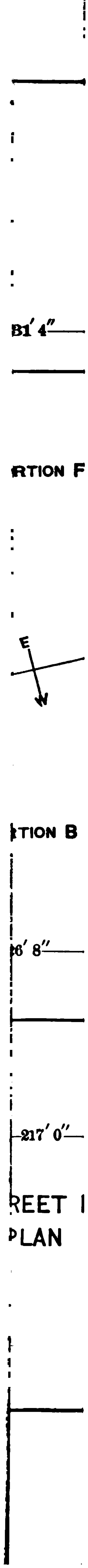
d
J
H

PLATE II

g. 6

MIDDLETOWN AND PORTLAND
BRIDGE,
DETAILS OF PIER 3.


31' 4"
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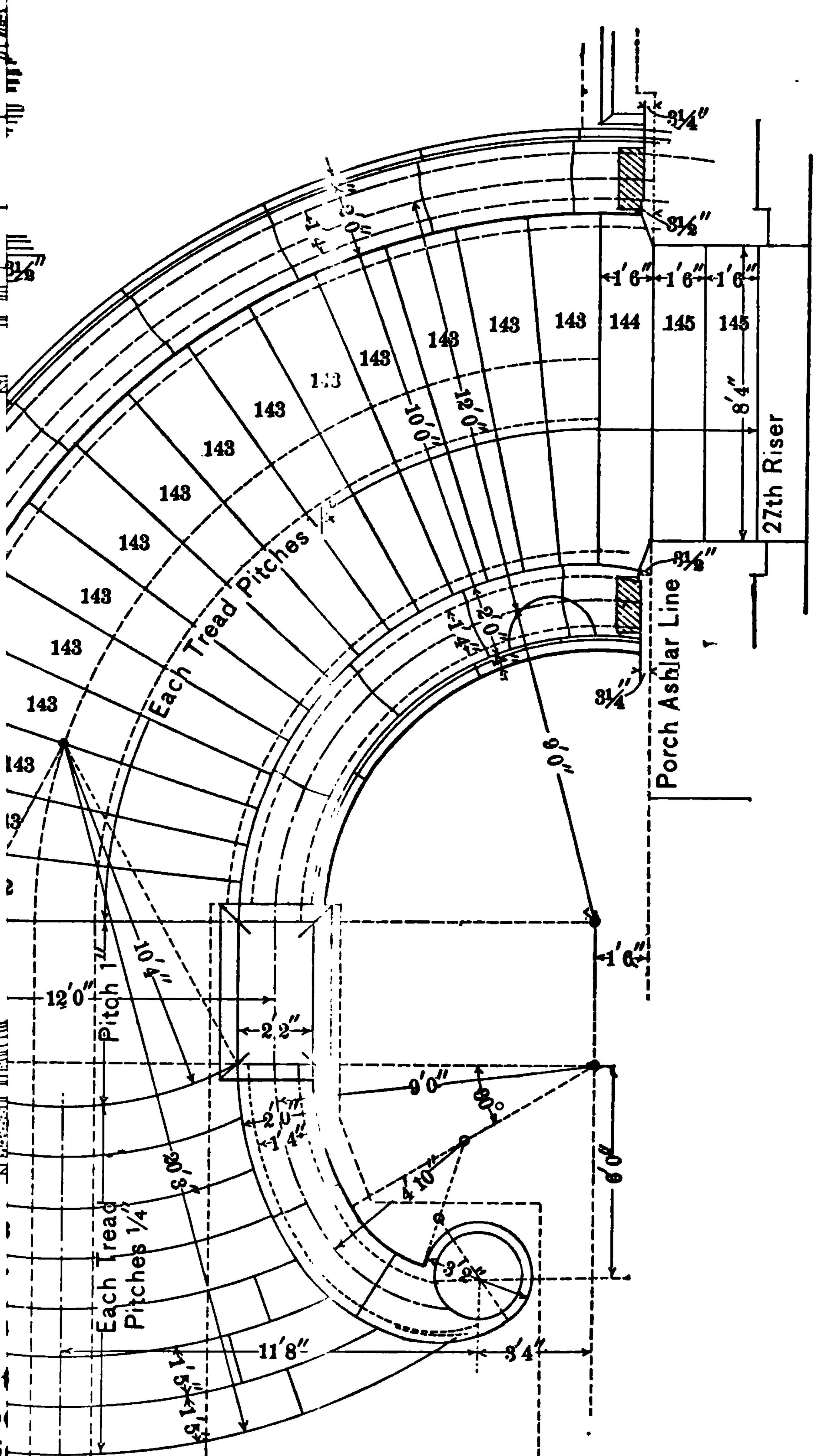
E
W
TION B
6' 8"
217' 0"
REET
PLAN


3
1
1-3
NINGS


3¼″
3½″
1′6″
1′6″
1′6″
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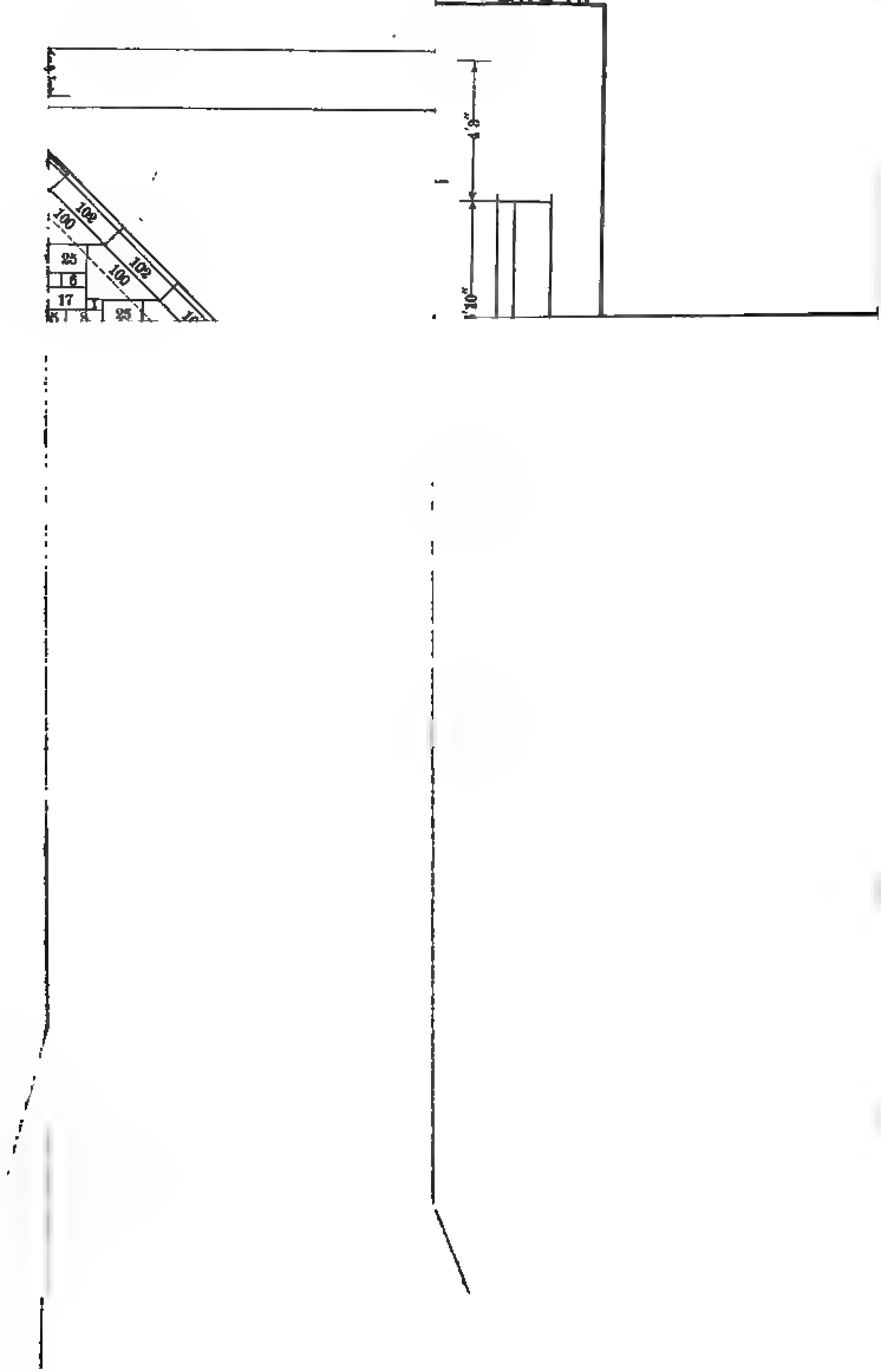
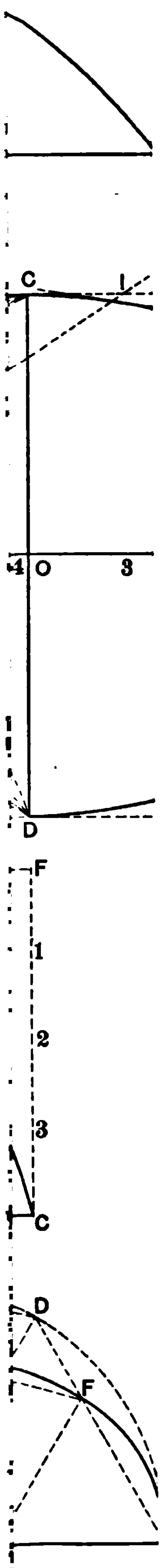
144
145
145
8′4″
27th Riser
12′0″
10′0″
Each Tread Pitches 1¼″
2′0″
1′4″
3½″
9′0″
3¼″
Porch Ashlar Line
1′6″
12′0″
Pitch 1″
10′4″
2′2″
9′0″
30°
2′0″
1′4″
4′10″
6′0″
20′3″
Each Tread Pitches 1/4
3′2″
11′8″
3′4″
1′5″
1′5″
Fig. 10

PLATE VII





g. 25

PLAN

DEVELOPMENT OF SOFFIT

Fig. 43

Fig. 44

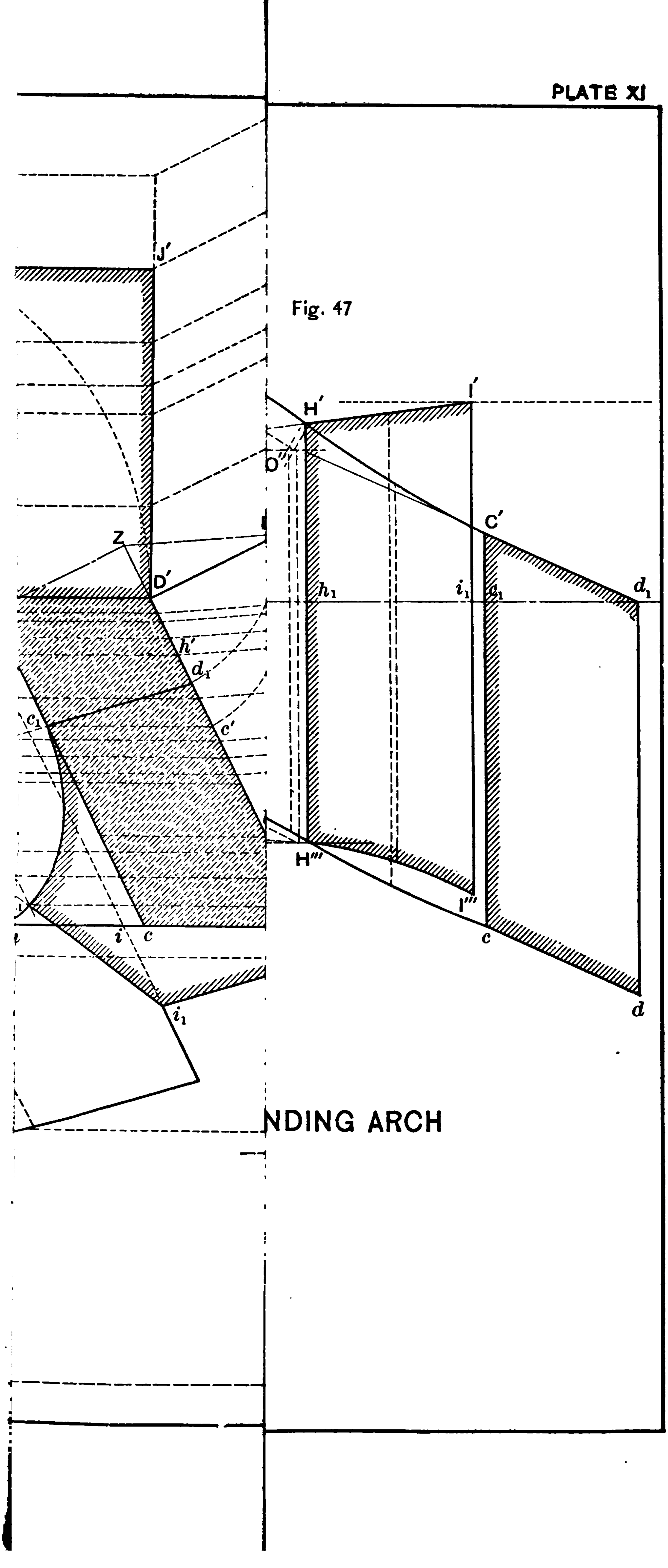
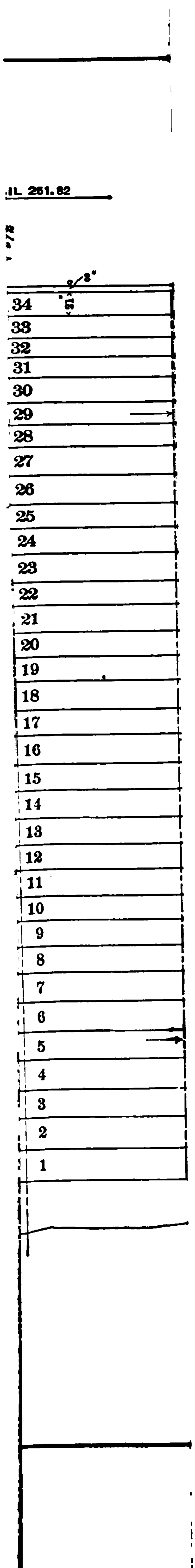


Fig. 47

NDING ARCH



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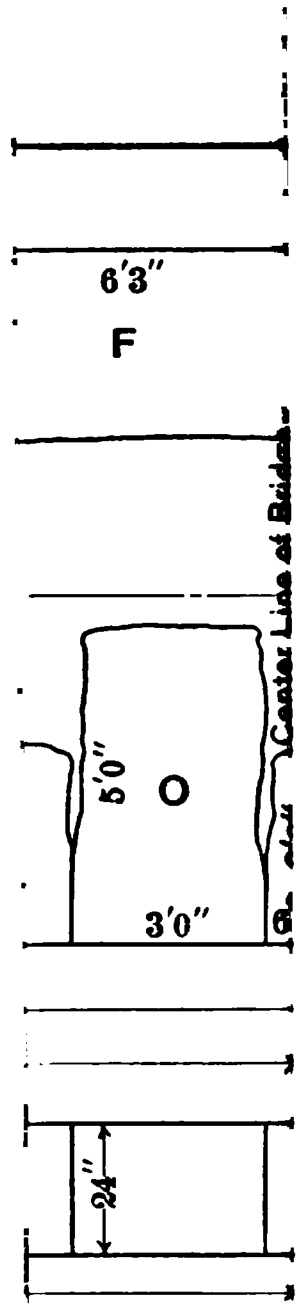
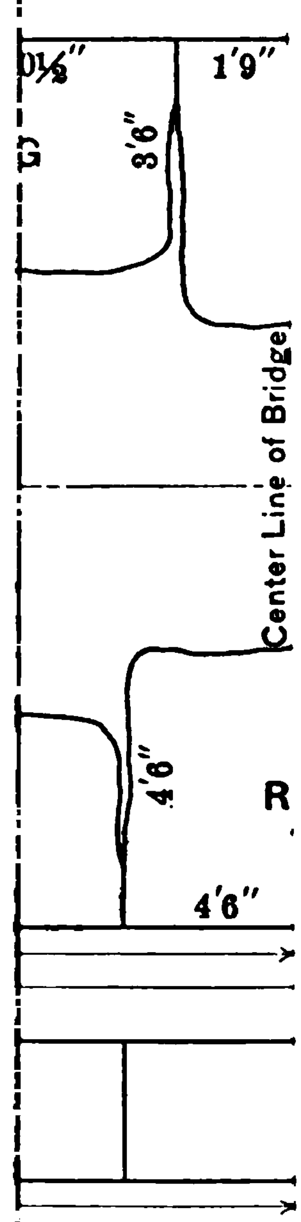


beds of stones.



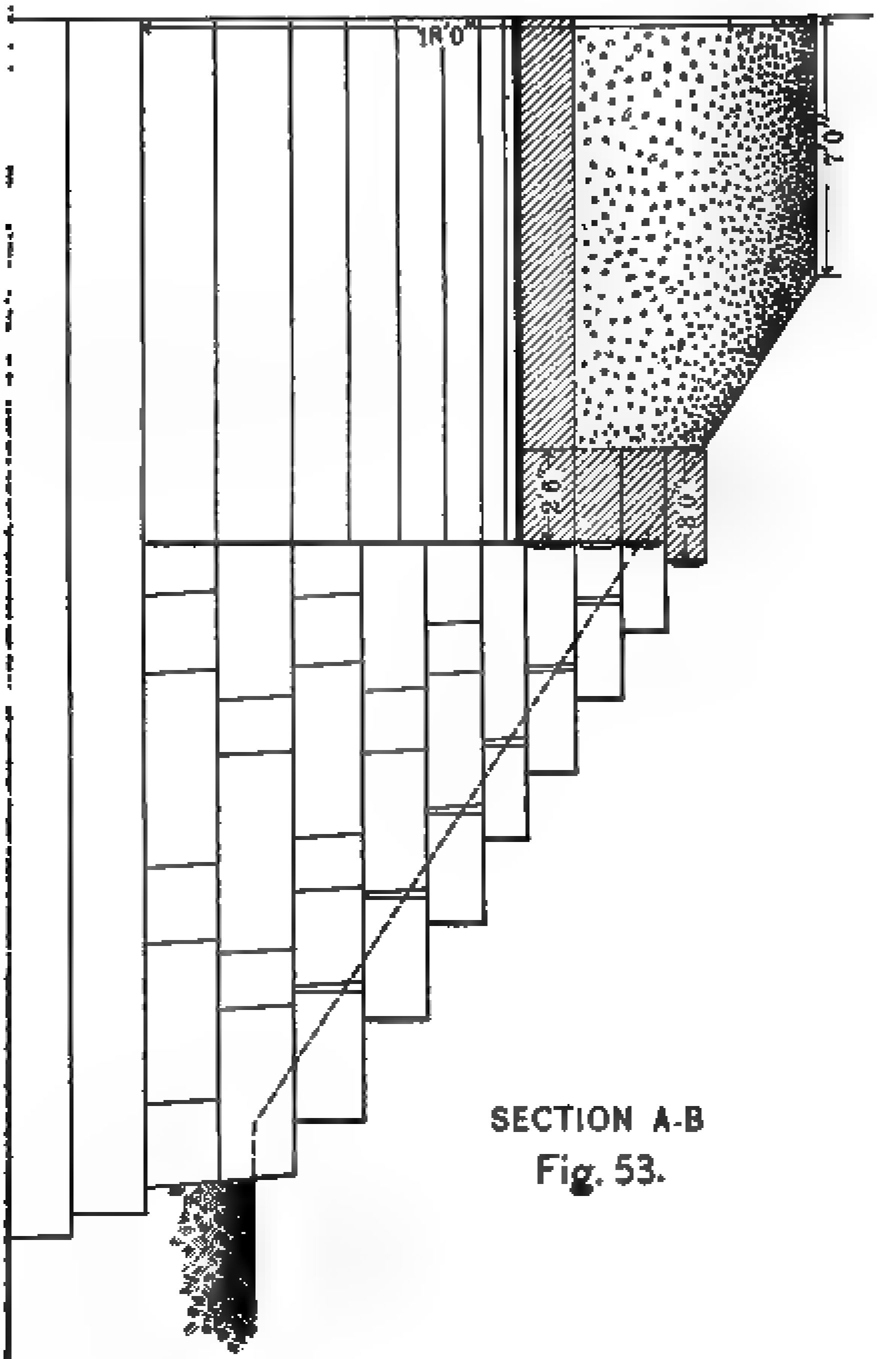
tones.

3 & 4.

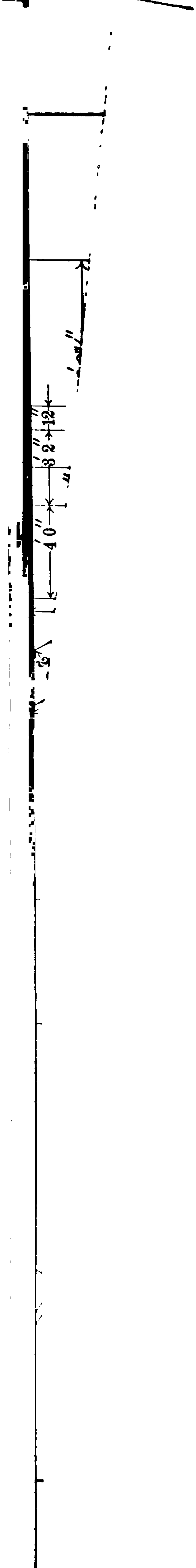
ARCH CULVERT.

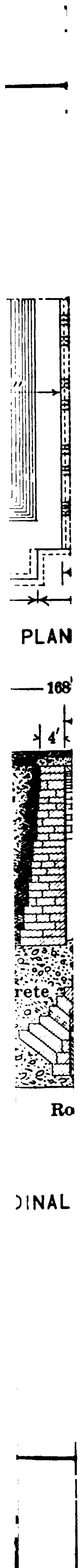
NOTE. Batter of front face of wing wall 2" to 1'.

CROSS SECTION.



SECTION A-B
Fig. 53.


12"
3 2"
4 0"


PLAN
168'
4'
rete
Ro
INAL

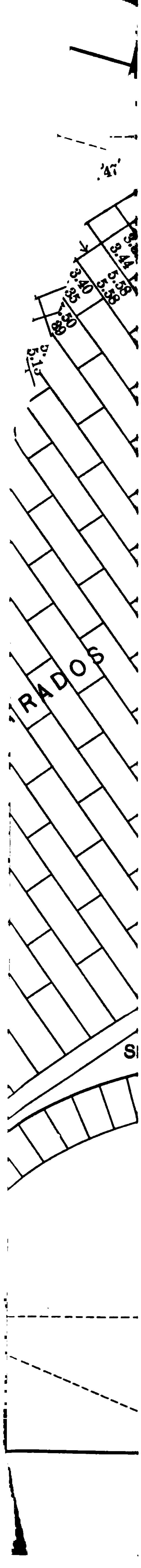

3.44
5.58
3.40
RADOS

Plate XIX

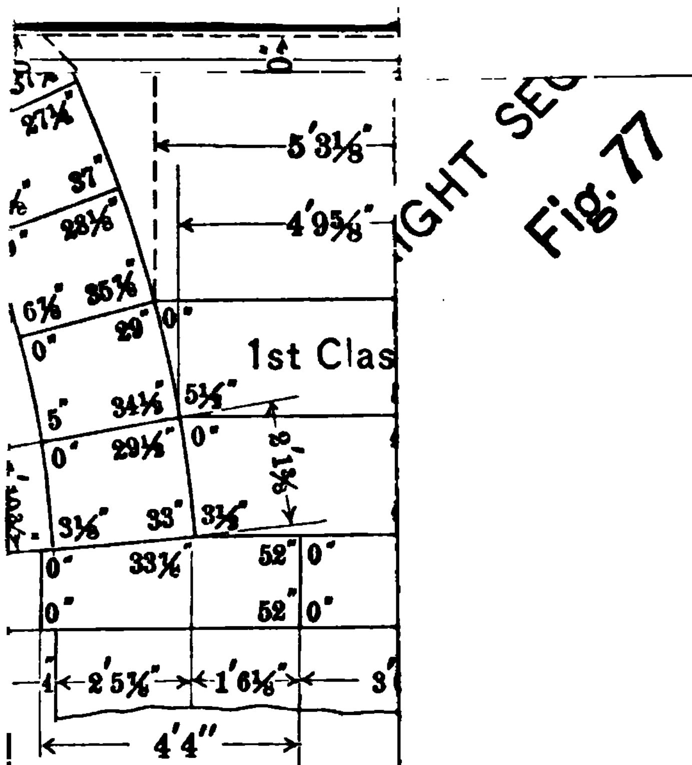


Fig. 77

ES WITH AXIS

n voussoirs m
of 8 inches m
nust be at leas
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centre except f
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class masonry.
ch third-class
feet 5 inches.
be provided wi

R. R.

RCH

ASS.

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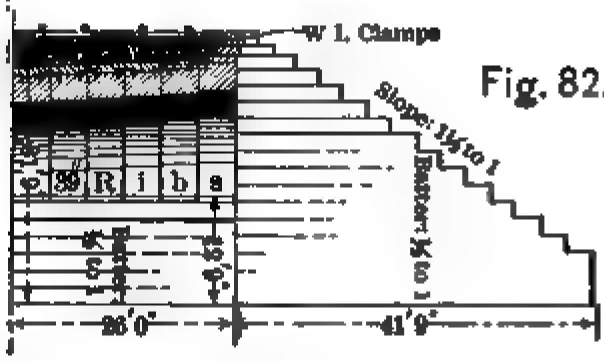


Fig. 82.

ECTION OF SKEW ARCH, TRENTON BRIDGE,
SYLVANIA R. R.

PLATE XXI

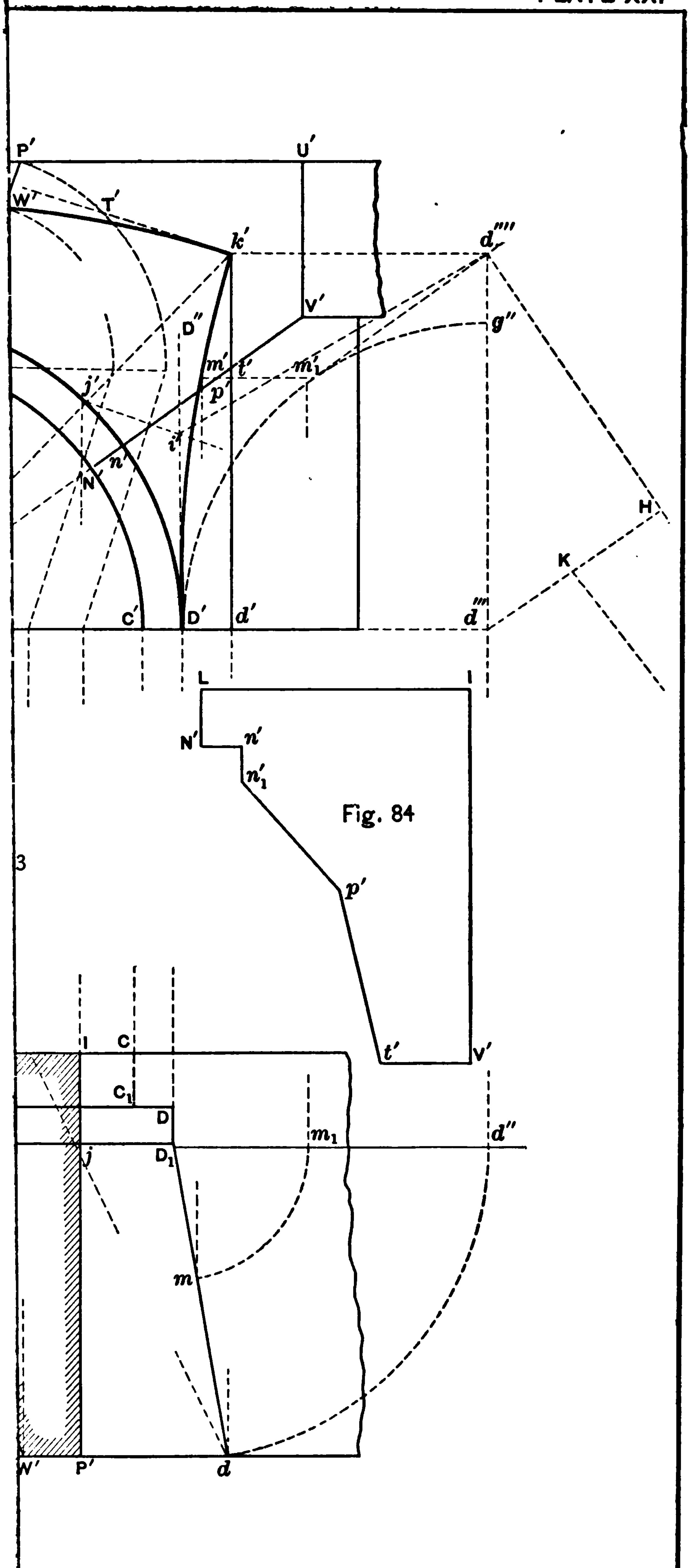
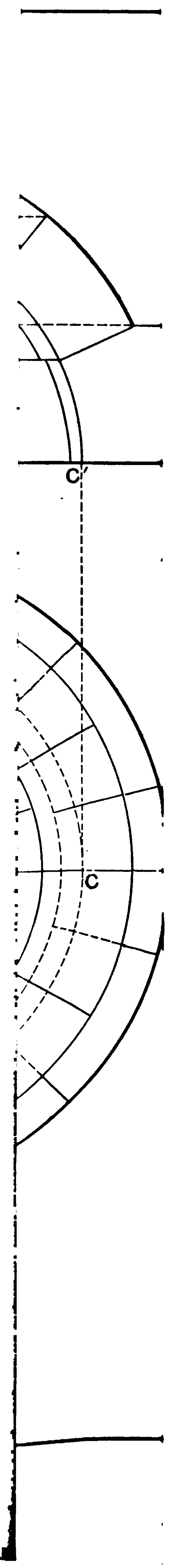


Fig. 84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